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SOURCES AND CHARACTERIZATION OF FINE PARTICULATE TEST DUSTS

W. H. Hedley, et al

Monsanto Research Corporation

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Dust	Stationary Sources	11G
Tests	Fine Particulates	14B
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Properties		
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ABSTRACT

To assist the research efforts in applied R&D in fine particle collection and simulation of industrial sources by the Control Systems Laboratory of EPA and its contractors, an investigation was undertaken to select suitable characterization criteria for test dusts; determine procedures for obtaining, handling, and characterizing the dusts; and establish potential suppliers of test dusts. Seventeen suitable characterization criteria for test dusts were identified, and techniques were selected for obtaining values for each property defined. The criteria considered included size distribution; shape, surface area, and pore volume; chemical composition; density; wettability and moisture content; solubility; hardness, abrasiveness, and grindability; charge properties; dielectric properties; corrosiveness; optical properties; magnetic susceptibility; plus two other properties, carrier gas composition and solids loading. Potential industrial suppliers of test dusts for simulation purposes were identified for eleven industries; pulverized coal combustion, stoker-fired coal combustion, basic oxygen furnaces, open hearth furnaces, electric arc furnaces, metallurgical coke ovens, cement plants, municipal incineration, steel foundries, Kraft pulp mill recovery furnaces, and asphalt plants. The problem of producing a particulate-laden test flue gas was evaluated. Redispersion of collected dusts is favored over generation of fresh particulate. The establishment of a central coordinating logistics network for the acquisition and characterization of test dusts is recommended.

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SECTION 1

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

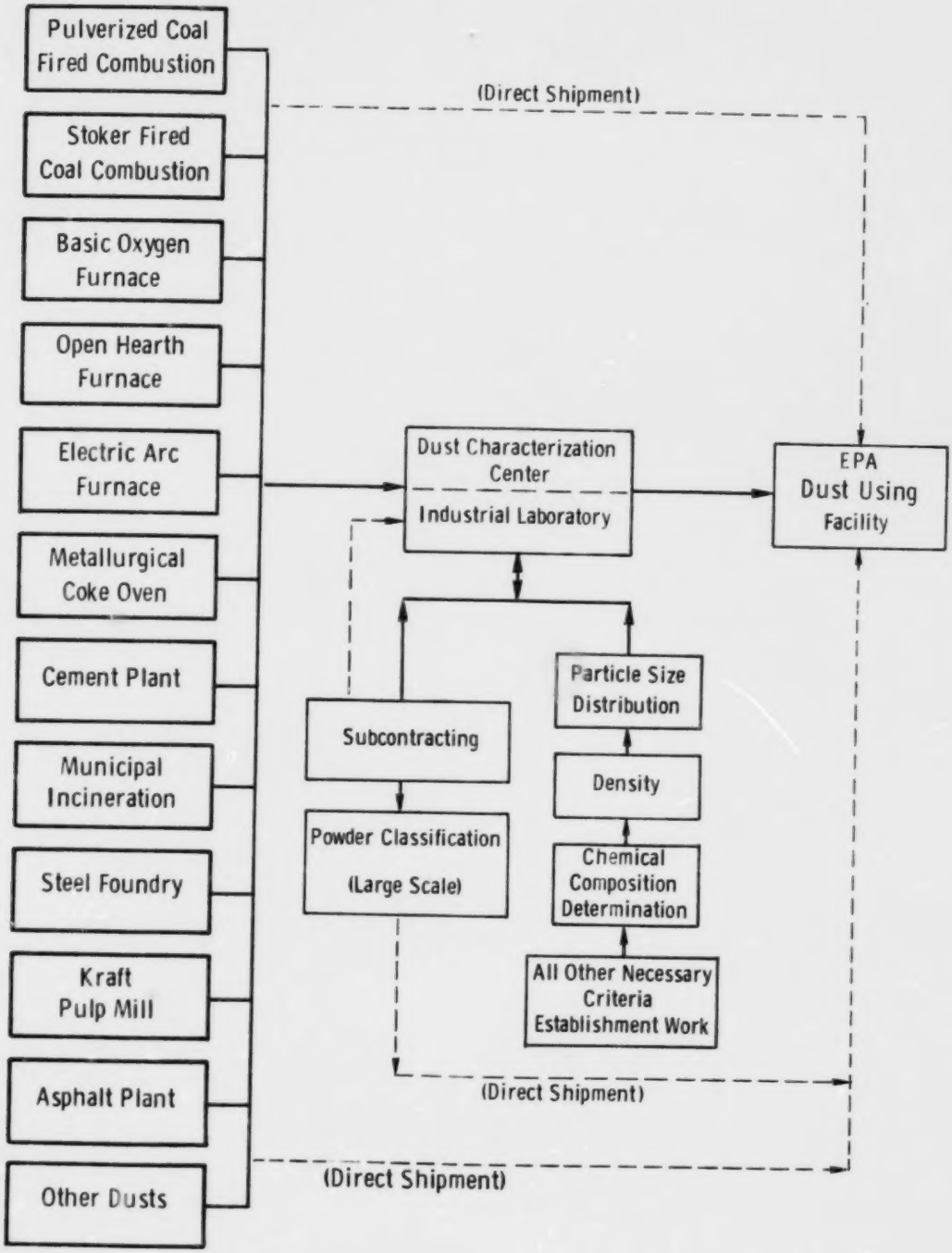
As a result of our investigation during this task, MRC concludes that securing adequate quantities of well-characterized particulates to fulfill the testing requirements of the Control System Laboratory can be accomplished by utilizing collected dust for redispersion from most industries of interest.

The test dusts can be characterized on many levels. Values for these characterization criteria may be obtained from a well-equipped analytical laboratory. The dust may be characterized to any level desired, but to keep cost at a minimum the variables and particulate properties required for each specific experiment must be carefully defined.

To provide a suitable test dust in the most efficient and economical way requires a well organized network of industrial contacts and a wide variety of analytical capabilities. Assuming that no one company can serve as a source of supply for all types of dust required, the most efficient system would establish a central coordination logistics network to arrange for the acquisition and characterization of the needed particulate samples. This operation would optimize utilization of the talents and capabilities of the test dusts sources, the EPA, and the appropriate industrial contractors.

Working relationships with the various potential dust sources, which are discussed in Section 3, could be established according to a framework similar to that shown in Figure 1. Within this framework several alternatives exist to maximize efficiency and minimize cost. Depending on the requirements for the test dusts, samples might be sent directly from their source to the Control Systems Laboratory or its contractors,

Figure 1. Potential Dust Acquisition System



they might go through a central coordinating facility and industrial laboratory for characterization, or for special requirements beyond the capabilities of the central facility, the test dusts might be channeled to an appropriate subcontractor enroute to their destination.

RECOMMENDATIONS

Creation of a flue gas suitable for fine particulate investigation appears to be feasible by redispersion of collected particulate using fluidized bed techniques. However, to ensure the applicability of this technique for the varied particulate sources of interest, further investigation is recommended. The effect of the radioactive charge neutralizer, the influence of a metallic fluidized bed redispersion column, the grain loading obtainable, and the applicability of alternative redispersion techniques should be identified.

Once the aforementioned reservations concerning redispersion of the dust are removed, it is recommended that the Control Systems Laboratory of EPA seek a contractor to establish a central coordination logistics network to acquire and characterize test dusts. The system could be similar to that described in Figure 1, and should be capable of acquiring, characterizing, and distributing ample quantities of test dust for the experimental programs of the Control Systems Laboratory and its contractors.

The contractor should be equipped to characterize particulate with regard to most if not all of the properties listed in Table 1, and described in Appendix A. A contractor with contacts among members of the industries listed in Figure 1 would also be beneficial in expediting the establishment and operation of a dust acquisition system. An industrial coordinator/supplier with numerous established industrial contacts for dust acquisition, extensive analytical capabilities for dust characterization, and a history of working with EPA and other government agencies would be ideal for this task.

Table 1. RELATIVE IMPORTANCE OF FINE PARTICLE CHARACTERIZATION

Property	Collection Device				Common Instrumentation for size analysis				
	High energy wet scrubber	Electrostatic precipitator	Fabric filter	Redispersion	Mechanical	Optical	Electrical	Thermal	Physico-chemical
Size distribution	P	P	P	P	P	P	P	P	P
Shape, surface area, pore volume	S	S	P	S	S	P	P	L	S
Chemical composition	S	S	S	S	S	S	S	S	S
Density	P	P	P	P	P	L	S	S	L
Wettability and moisture content	S	P	P	P	L	L	L	L	P
Solubility	S	S	S	L	L	L	L	L	L
Hardness, abrasiveness, grindability	L	L	S	P	L	L	L	L	L
Charge Properties	S	S	S	P	S	L	P	L	L
Dielectric properties	S	P	P	P	S	L	P	L	L
Corrosiveness	P	S	S	L	L	L	L	L	S
Optical properties	L	L	L	L	L	P	L	L	S
Magnetic susceptibility	L	L	L	P	L	L	L	L	L

P = primary importance
S = secondary importance
L = little or no importance

SECTION 2

INTRODUCTION

The Control Systems Laboratory of the Environmental Protection Agency (EPA) has been involved in evaluation and improvement of particulate measuring and control devices for several years. Now, with increased emphasis being placed on particle size, (especially fine particles less than five microns in size), it is necessary to establish sources of reproducible, well characterized, fine particulates for experimentation in this field. The test dusts are to be used for two general purposes: (1) applied R&D in fine particle collection, and (2) simulation of industrial sources. Test particles are presently available from Dow, glass spheres from NBS, AC test dusts, and ASME test dusts, but due to their costs, quantity purchase is prohibitive. Consequently, an alternative source of test dusts is desirable.

To assist in this effort, an investigation was undertaken to select suitable criteria for test dusts; to determine procedures for obtaining, handling, and characterizing the dusts; and to establish potential suppliers of test dusts.

Suitable dust characterization criteria were selected by considering the relative importance of the various criteria on conventional collection equipment, redispersion requirements, and common size-measuring instrumentation. The dust properties considered were: size distribution; shape, surface area, and pore volume; chemical composition; density; wettability and moisture content; solubility; hardness, abrasiveness, and grindability; charge properties; dielectric properties; corrosiveness; optical properties; and magnetic susceptibility. Carrier gas composition and solids loading were also considered. Discussion of these properties and their relative importance to the three areas mentioned above appears in Appendix A, Selection of Dust Characterization Criteria, while Appendix B, Dust Characterization Techniques, identifies potential techniques for measurement of each dust characteristic.

Section 3 entitled Potential Dust Sources identifies possible suppliers of test dusts for the simulation of industrial sources. Potential suppliers were identified for the following sources: (1) pulverized coal combustion, (2) stoker-fired coal combustion, (3) basic oxygen furnace, (4) open hearth furnace, (5) electric arc furnace, (6) metallurgical coke oven, (7) cement plant, (8) municipal incineration, (9) steel foundry, (10) Kraft pulp mill recovery furnace, and (11) asphalt plant.

Two examples of the cost and time required to provide quantities of well characterized test dusts follow in Section 4, Preliminary Cost and Time Requirements for Acquisition and Characterization of Test Dusts. Estimates of the cost to acquire and characterize test dusts for each of the characterization criteria are provided for samples of flyash from pulverized coal combustion and particulate from municipal incineration.

The final section, Selection of Dust Dispersion Method, addresses the problem of establishing a particulate laden test gas. Two techniques for creating a dust dispersion, generation or redispersion, were considered and redispersion is recommended. As support for this position a simple qualitative experiment was conducted using a fluidized bed of $\sim$100 μ glass beads or nickel beads to successfully redisperse flyash or iron oxide particulate.

SECTION 3

POTENTIAL DUST SOURCES

For much of the fine particulate research being proposed by EPA, a representation or simulation of industrial effluents is required. To produce these simulated flue gases, sources of dust supplies must be secured. The fine particulate sources of greatest interest to EPA at present are combustion processes and iron and steel furnaces. For combustion processes both pulverized coal-fired and stoker-fired coal combustion methods are of interest, and in the iron and steel industry basic oxygen furnaces, open hearth furnaces, electric arc furnaces, and metallurgical coke ovens are also of interest. Other sources of fine particulate emissions of interest are cement plants, municipal incinerators, steel foundries, Kraft pulp mill recovery furnaces, and asphalt plants. Several potential industrial sources of test dusts were contacted. The results of these contacts are summarized in Table 2.

The Dayton Power and Light Company operates both pulverized and stoker-fired coal combustion electric power generation facilities, and is a potential dust supplier. No difficulties are anticipated in obtaining quantities of test dust for redispersion from both type facilities.

Bethlehem Steel Corporation operates several basic oxygen furnaces in Sparrow's Point, Maryland; Bethlehem, Pennsylvania; and Burns Harbor, Indiana. Particulate control is accomplished with electrostatic precipitation. Quantities would be available if handling and shipping problems can be solved.

Open hearth furnaces operated by Bethlehem Steel Corporation in Sparrow's Point, Maryland; Johnstown, Pennsylvania; and Lackawanna, New York utilize electrostatic precipitators for particulate emission control. One shop at Sparrow's Point used fabric filtration but is no longer in operation. The collected material may be acquired for redispersion testing.

Table 2
POTENTIAL DUST SUPPLIERS

Industry	Company	Contact
Pulverized and stoker fired coal combustion	Dayton Power and Light Company Dayton, Ohio (513) 222-0441	Mr. H. Palmer
Basic oxygen furnace	Bethlehem Steel Corporation Bethlehem, Pennsylvania (215) 694-3676	Mr. J. Leming
Open hearth furnace	Bethlehem Steel Corporation Bethlehem, Pennsylvania (215) 694-3676	Mr. J. Leming
Electric arc furnace	Bethlehem Steel Corporation Bethlehem, Pennsylvania (215) 694-3676	Mr. J. Leming
	Inland Steel Company East Chicago, Indiana (219) 392-1200	Mr. J. Brough
Cement plant	Southwestern Portland Cement Company Fairborn, Ohio (513) 878-8651	Mr. J. Dorn
Municipal incineration	City of Braintree Waste-Disposal Department Braintree, Massachusetts (617) 843-6209	Mr. Courchene
	Chicago Northwest Incinerator Chicago, Illinois (312) 744-4571	Mr. Groszek
Steel foundry	Dayton Steel Foundry Company Dayton Walther Corporation Dayton, Ohio (513) 296-3113	Mr. F. Fensel
Kraft pulp mill recovery furnace	Mead Corporation Chillicothe, Ohio (614) 772-3111	Mr. W. Lapp
Asphalt Plant	Valley Asphalt Corporation Dayton, Ohio (513) 293-4119	Mr. M. Levy

Fabric filters are used to control particulate emissions from several of Bethlehem Steel Corporation's electric arc furnaces. Another potential source of fine particles from an electric arc furnace is the Inland Steel Company's East Chicago, Indiana plant. The collected material is stored until an adequate amount is accumulated at which time it is wetted to cause agglomeration and then removed to a landfill. Quantities may be collected before wetting and are available as needed from either source.

The search for a potential supplier of collected coke particulate emissions was abandoned after numerous contacts and continued discouraging comments on the subject. (Contacts were made with American Iron and Steel Institute, Bethlehem Steel Corporation, National Steel Corporation, Inland Steel Company, and Great Lakes Carbon Corporation). Collection equipment is not common and where used is generally of the wet scrubbing variety.[1] Consequently, simulation of metallurgical coke ovens may require generation of test dusts.

Southwestern Portland Cement Company of Fairborn, Ohio is a dry process Portland cement manufacturer. Their emissions are controlled by an electrostatic precipitator. Unlimited quantities of their collected dust are available.

Both the Braintree, Massachusetts and Chicago Northwest municipal incinerators utilize electrostatic precipitation for particulate collection. The collected material is currently landfilled. Quantities of the collected material are available from either of these sources.

The Dayton Steel Foundry Company of Dayton Walther Corporation operates an electric arc furnace controlled by a high efficiency fabric filter. The collected material is discarded as waste. Consequently, they are willing to provide quantities of the collected material upon request.

The Mead Corporation operates a kraft pulp mill in Chillicothe, Ohio. The emissions from the recovery furnace are controlled by a low efficiency electrostatic precipitator. Samples of the collected material could be obtained.

Valley Asphalt Corporation of Dayton, Ohio operates sand and gravel based asphalt plants. Three of their plants in the Cincinnati area use fabric filters to collect fine particulate emissions. Quantities of the collected material could be obtained.

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1. Anon., "A Search for Clean Coking Processes," Steel Facts, Number 224, 10-11 (January 1974).

For the industries where the collected particulate does not adequately represent the small end of the particle size distribution, auxiliary particulate collection is possible. For example, a high efficiency mobile fabric filter could be applied to a side stream to collect fine particulate for augmentation of the already collected material. Also, to meet specific size requirements classification of collected dusts as shown in Figure 1 may also be performed.

SECTION 4

PRELIMINARY COST AND TIME REQUIREMENTS FOR ACQUISITION AND CHARACTERIZATION OF TEST DUSTS

Cost and time requirements for MRC to provide quantities of test dusts are estimated below. These figures are preliminary estimates and are to be used only to establish a cost range for the acquisition of test dusts suitable for research and development efforts.

Two dust sources have been arbitrarily selected as typical examples of a request for test dust so that costs may be estimated. The two sources are (1) a pulverized coal fired utility boiler in Dayton, Ohio, and (2) a municipal incinerator in Chicago, Illinois. The cost of the test dust on a per pound basis is proportional to the quantity of dust provided, with smaller quantities being more expensive. To establish a basis for this cost estimate we have assumed that 1000* pounds of each test dust as collected at the industrial site have been requested.

Table 3 presents the cost of obtaining a 1000-pound quantity of test dust from its source. For the pulverized boiler the cost for obtaining the dust is $228 while the cost for municipal incineration dust is $1525. Notice that the bulk of the dust acquisition cost is encounted in the manpower requirements to collect the dust and return it to the characterization center. Depending on the geographical orientation of the source, characterization center, and destination of the test dust; the dust might be returned to the characterization center or sent directly to its destination with small samples retained for characterization purposes. The dust may be carried in the dust acquisition vehicle or may be sent by common carrier.

*See Appendix E, Metric Conversion Table, for metric equivalents of English units.

Table 3. DUST ACQUISITION COSTS FOR 1,000 POUNDS OF TEST DUST

	Flyash from Pulverized Coal Utility Boiler Dayton, Ohio		ESP Waste from Municipal Incinerator Chicago, Illinois	
Charges for material and container	$1 per 50 lb, flyash	$ 20	$0.50 per 50 lb particulate	$ 10
Labor	2 men for ½ day ($25/hr)	200	2 men for 3 days	1200
Subsistence	no charge		2 nights, 3 days	180
Truck	$15/day, 15¢/mile	8	$15/day, 15¢/mile	135
Total ($)		$228		$1525
($/lb)		0.228		1.525

We have assumed for our estimate that the 1000 pounds of test dust are returned to the dust characterization center by the dust acquisition team.

The dust must then be characterized as specified by the user's request. Table 4 presents estimated typical charges for characterization of each sample. Depending on user specifications, multiple samples might be required, increasing the per pound cost of the test dust. However, the increased cost will not be linear in nature due to the economy achieved in scale.

The total cost for 1000 pounds of flyash or incinerator ESP waste will be a combination of the figures in Tables 3 and 4 depending on the level of characterization and number of test samples required for characterization.

The time required to provide quantities of adequately characterized dusts suitable for experimental work depends on several factors. The quantity of dust requested and the location of the source of the dust will influence the time required for actual dust acquisition. The level of dust characterization requested will also influence time requirements; more characterization criteria or multiple samples would require additional time. In any case, three weeks would be adequate to acquire, characterize, and prepare for shipment a quantity of test dust suitable for experimentation. The time required between receipt of a request for test dust and shipment of the product dust may possibly be shortened by the establishment and maintenance of a stock of test dusts to be drawn upon as needed.

Table 4. DUST CHARACTERIZATION COSTS FOR EACH SAMPLE

Property	Cost ($/sample) (June 1974)
Size Distribution (primary particles)	60
Shape**	170
Surface Area (BET)	70
Pore Volume	210
Chemical Composition	270
Density	40
Wettability (qualitative)	10
Moisture Content	40
Solubility	40
Hardness	40
Abrasiveness*	--
Corrosiveness*	--
Grindability	70
Dielectric Properties	200
Charge Properties	110
Magnetic Susceptibility	110
Optical Properties	410

*Due to the combined influence of flue gas and particulate on determination of abrasiveness and corrosiveness, these properties are best measured on an actual flue gas at the test facility.

**Cost for shape measurement includes the cost for size distribution, surface area, and density measurements.

SECTION 5

SELECTION OF DUST DISPERSION METHOD

5.1 GENERATION AND REDISPERSION

The test dusts will be used for two general purposes: (1) applied R&D in fine particle collection, and (2) simulation of industrial sources.

Two methods of providing dust dispersions for the simulation of industrial sources are (a) generation of dust from a parent material, and (b) redispersion of an existing dust collected from industrial effluent of interest. The objective is to produce a dust stream which is almost identical in all respects to those existing in the stack. It appears that neither generation nor redispersion would reproduce a dust stream (in the laboratory) which is identical to large-scale industrial effluent.

If dust is generated from a parent material in a small-scale furnace or other facility (e.g. plasma jet, rotary kiln, etc.), the resultant product may not simulate exactly the industrial effluent. The dust characteristics can change with the size of furnace and process design. For example, the effect of process design (firing method) on the size distributions from pulverized coal combustion and stoker-fired coal combustion (see Appendix C) are the result of different gas velocities, temperature, and residence time in the furnace. The effect also extends to density and chemical composition because the time-temperature relationships influence the burnout of carbon and the fusion of the mineral components. In the iron and steel industry, emissions from open hearth furnaces and basic oxygen furnaces are very different in size, shape, density, and resistivity as the result of the design and operation of the two types of furnaces. Reported particle size distribution measurements from several power plant installations indicate that boiler furnace and operating conditions

are the most important factors in determining fly ash particle size.[2]

In addition to difficulty in industrial effluent simulation, dust generation is also complex and expensive. This is not to say that redispersion of an existing dust is without any problem. On the other hand, it would be difficult to redisperse extremely fine particles (as found in basic oxygen furnace and electric arc furnace operations) or sticky particles (as probably found in metallurgical coke oven operation) by any of the redispersion methods.

To ease the comparison of dust handling techniques, the advantages and disadvantages of generation and redispersion are listed in Table 5. The primary advantage of generation is freshness of generated particles. This is important when certain surface characteristics become important or when extrafine dust is not obtainable by redispersion of existing dust. However, for the majority of industrial effluents, the laboratory simulation can be achieved by means of a redispersion technique. Based on our past experience (e.g. sampling and laboratory redispersion) and the analysis of the problem, handling techniques suitable for simulation of various industries of interest were classified and are listed in Table 6.

Among the many ways to redisperse existing dust are the following:

(a) fluidization
(b) jet mill dispersion
(c) combustion or explosion of dust-fuel mixture
(d) atomization of liquid suspension and evaporation
(e) air-blast powder dissemination

Applicability of these dispersion methods to various industries is also shown in Table 6.

Several generation techniques which may be suitable for simulation of industrial effluent are:

(a) electric arc furnace
(b) rotary kiln
(c) plasma jet, etc.

Their applicability is also listed in Table 6.

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2. Anon., "Criteria for the Application of Dust Collectors to Coal Fired Boilers," IGCI/ABMA Joint Technical Committee Survey, April, 1965.

Table 5. ADVANTAGES AND DISADVANTAGES OF GENERATION AND REDISPERSION OF FINE DUST

	Generation	Redispersion
Advantages	1. Dusts are freshly formed	1. Equipment relatively inexpensive
	2. Similar carrier gas (not necessarily exact)	2. Versatile, same equipment for many different dusts
	3. No need for dispersion	3. Easy for government contractors to duplicate the system
		4. Same chemical composition
		5. Same primary particle size
		6. Most of dusts are readily available from bag house or precipitator of various industries
Disadvantages	1. Expensive (equipment and operation)	1. Not fresh dust surface (aging effect)
	2. Not exactly the same aggregate size distribution	2. Not exactly the same aggregate size distribution
	3. Need different equipment for different dust	3. Need dispersion and sometimes difficult to disperse extra fine or sticky dust
	4. Need exact composite raw materials for furnaces	4. Need gas conditioning (e.g. composition and humidity, etc.)
	5. Not necessarily the same chemical composition	5. Need collection of dust from sources
	6. Not necessarily the same primary particle size	
	7. Expensive to duplicate the system	

Table 6. SUITABLE DUST DISPERSION TECHNIQUES

	Industry	Generation	Redispersion
1	Pulverized Coal Combustion	L (K)	P (F, J)
2	Stoker Fired Coal Combustion	L (K)	P (F, J)
3	Open Hearth Furnace	L (K)	P (F, J)
4	Basic Oxygen Furnace	P (E)	L (C, J, F)
5	Electric Arc Furnace	P (E)	L (C, F)
6	Metallurgical Coke Oven	P (E)	L
7	Cement Plant	L (K)	P (F, J)
8	Kraft Pulp Mill	L (K)	P (F, J)
9	Asphalt Plant	L (K)	P (F, J)
10	Municipal Incineration	L (K)	P (F, J)
11	Steel Foundry	L (E)	P (F, J)

P --- Preferred
L --- Less Preferred

Redispersion
- F --- Fluidized bed
- J --- Jet mill
- C --- Combustion

Generation
- E --- Electric arc furnace
- K --- Rotary kiln

5.2 PREFERABLE DUST DISPERSION TECHNIQUES

In the previous section various methods of generation and redispersion techniques were listed. It would be very difficult for a single piece of equipment to disperse the dust (either by generation or redispersion) and simulate all 11 industries listed in Table 6. It would be desirable to use a single redispersion technique (e.g. fluidized bed) for a majority of the industries. For the simulation of one or two other industries, a different generation scheme may be needed. For example, it would be very difficult to redisperse a mixture of tar-like or oily dust by a redispersion technique.

Among the many techniques listed in the previous section, some of the more promising ones are discussed below.

5.2.1 Fluidized Bed

The fluidized bed appears to be particularly suitable for dust dispersion because it deagglomerates the dust and at the same time acts as a capacitor, thereby damping out unsteady dust feedings into the bed. When a mixture of dust and spherical beads is exposed to upward airflow, the dust will mix and eventually elutriate out of the fluidized bed. The dust should have an average aerodynamic diameter one order of magnitude smaller than the bed solids.

In order to minimize electrostatic charging, the fluidized bed column and the bed solids should be made from electrically conducting materials (e.g. metal). Bed solid materials should also have the following properties: (a) smooth, spherical shape, (b) hard material, low abrasion, (c) inert at operation temperatures and pressures, no corrosion or oxidation, (d) no gas or liquid adsorption, (e) low electrical charging effects.

Successful dispersion of several dusts (fly ash, coal dust, and air cleaner test dust) by fluidized bed is reported by K. Willeke and co-workers at the Particle Technology Laboratory of University of Minnesota.[3] The results of their work are shown in Figure 2.

The quality of dispersion by fluidized bed was determined by comparing the dry dispersed dust from a fluidized bed with the same dust dispersed in the liquid. Considering an accuracy of 10 to 15% for the determination of the particle

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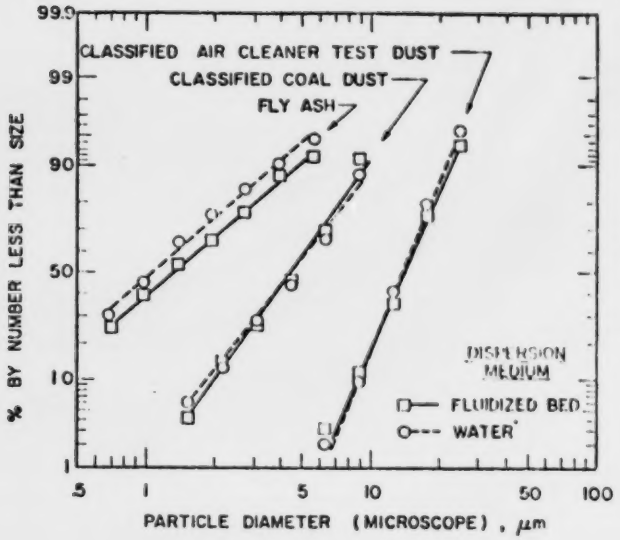
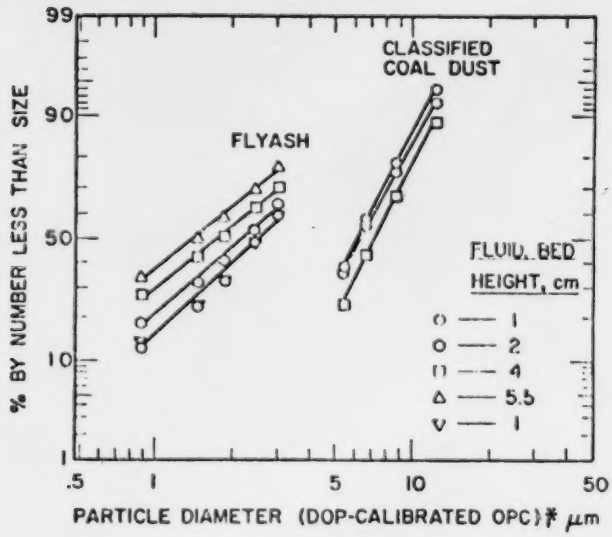
3. Willeke, K., Lo, C. S. K., and Whitby, K. T., "Dispersion Characteristics of a Fluidized Bed," Particle Technology Laboratory Publication No. 217, Particle Technology Laboratory, Mechanical Engineering Department, University of Minnesota, December 1973.





*OPC - optical particle counter

Figure 2. Size Distribution of Coal Dust, Fly Ash, and Test Dust Dispersed by Fluidized Bed and Water

number distribution under an optical microscope, the two dispersion techniques result in equal size distributions by number within experimental error. The fluidized bed appears to disperse well those dusts which do not cake appreciably. However, a fluidized bed may not sufficiently deagglomerate some aggregates such as carbon black.

A typical fluidized bed dust dispersion set-up is shown in Figure 3. Since the dynamics of the fluidized bed always electrically charges the effluent dust particles, a radioactive charge neutralizer is shown above the fluidized bed. In case the formation of charged strings of particle aggregate is desired, the neutralizer could be removed.

5.2.2 Jet Mill

In work on Brink® fiber beds and wet scrubbers, we have successfully redispersed submicron iron oxides and fly ash in our dust testing facility using jet mills and various dust feeders (such as the BIF Omega grooved disc dry feeder, Metco plasma flame spray feeder, TAFA powder feeder, SYLCO powder feeder, and vibrating trough feeder). Figure 4 is a schematic of our jet mill installation. Our past experience indicates that dispersing and feeding of submicron iron oxides is much more difficult than that of fly ash.

5.2.3 Combustion or Explosion of Dust-fuel Mixture

For extremely fine particles often it is much easier to disperse in a liquid phase than in a gas phase. To facilitate dispersion fuel (e.g. acetone) or some other explosive material may be used. The technique has been widely used in the dissemination of fine particulate matter (e.g. silver iodide) in work on atmospheric trace or weather modification studies. Desired dust may be mixed in a solution or flare material at proper concentration for dust redispersion purpose in the laboratory.

5.2.4 Electric Arc Furnace

Electric arc furnace or arc welding techniques have been used occasionally for producing fine metal fumes in the laboratory (e.g. at the University of Minnesota and the West Virginia University).[4] Fresh and highly charged fine particles (thread-like aggregate can be produced by this method. However, it

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4 . Personal Communication, Professor B. Linsky, West Virginia University, 4 February 1974.

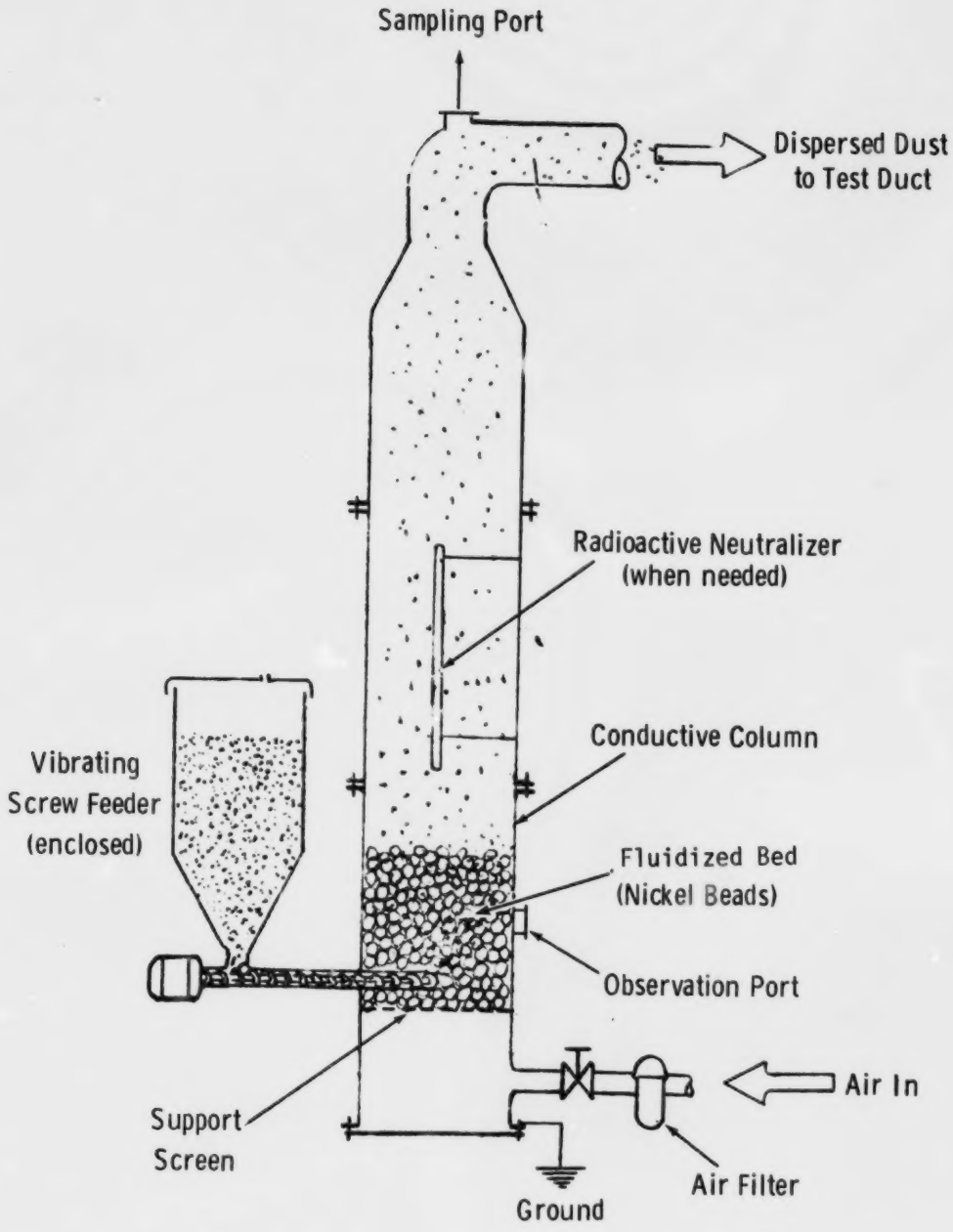


Figure 3. Schematic of Fluidized Bed Dust Dispersion System

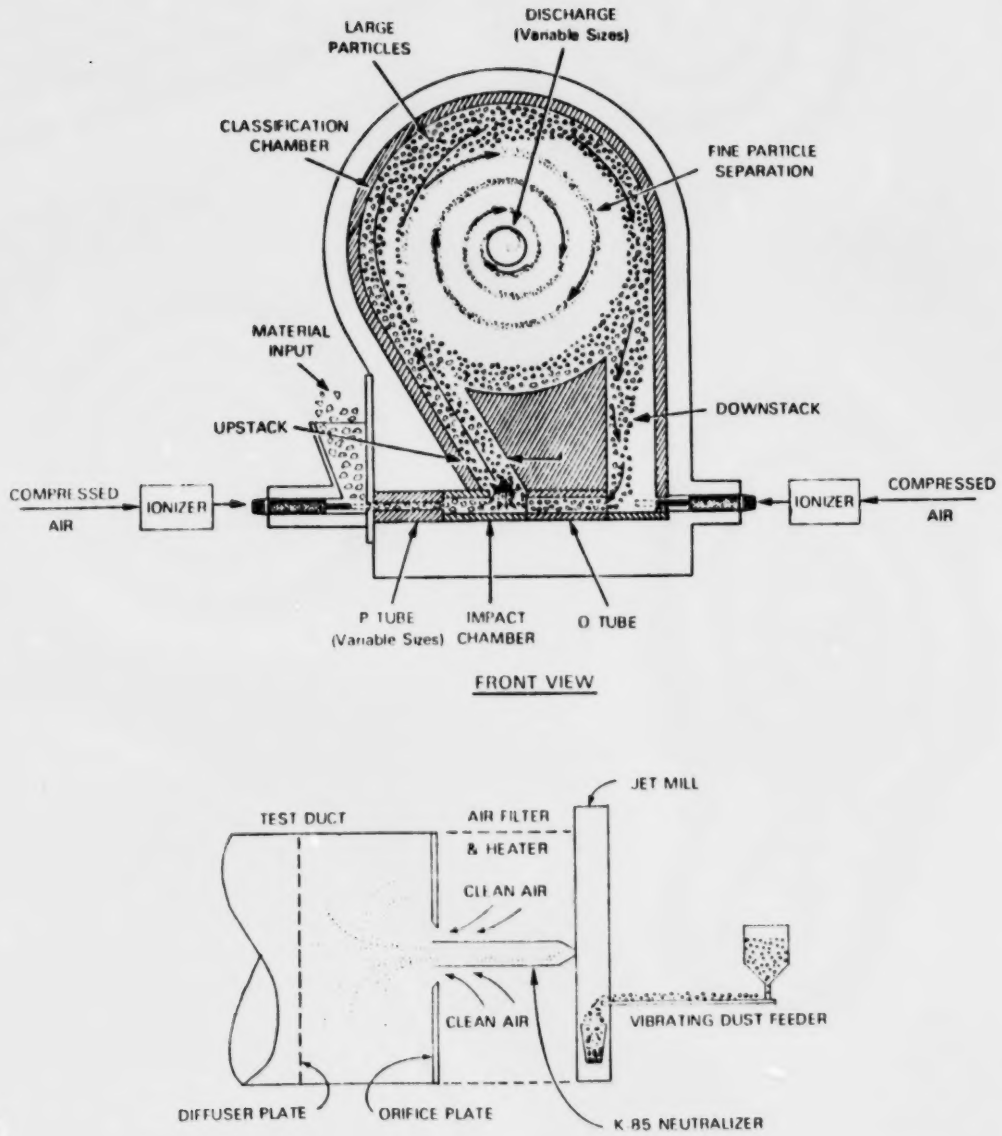


Figure 4. Schematic of Jet Mill Installation

would be difficult to produce a large quantity of dust to simulate grain loadings of an industrial stack, especially for a large test facility. Metals of special interest can be used as consumable electrodes to produce desired metal fumes.

5.2.5 Rotary Kiln

A small rotary kiln could be used to generate a variety of dusts by burning mixtures of materials of interest. As discussed in an earlier section, even with proper control of burning conditions (e.g. temperature) the resultant fresh dusts may not be identical to industrial effluent in particle size distribution or chemical composition. However, the equipment could be valuable in certain aspects of laboratory study.

5.3 JUSTIFICATION FOR REDISPERSION OF TEST DUSTS

5.3.1 Aging and Agglomeration

In order to understand the effect of aging on the production of fine particles, it may be helpful to examine the formation of particles in the combustion process. For example, when fumes and smokes are generated by combustion, the basic mechanism operating is usually that of vapor condensation. Because of the high temperatures involved and the rapidity of the reaction taking place, it is impossible to analyze the process in detail. Two types of primary particles form the reaction zone. One is crystalline in nature (such as perfect crystals of some metal oxides) and the other amorphous in nature (such as carbon smoke). After the particles leave the reaction zone, coagulation begins and aggregates are formed. Fine particles of submicron size tend to coagulate quite rapidly owing to their lively Brownian motion. Freshly formed fumes or smokes, therefore, exhibit great Brownian activity which brings individual particles into frequent contact. If the particles adhere on such contact, coagulation has occurred, and the particle size is thereby increased. As the average size increases, it is clear that the rate of coagulation decreases and the particle-size structure of the particulates becomes more stable.

When carbon smoke is produced by incomplete combustion, the small particles tend to form long chains or filaments. In the case of electric arc furnaces, metal vapor evolved at a very high temperature is cooled in the air stream and condenses to form a smoke. Oxidizable metals (e.g. cadmium,

lead, copper, manganese, chromium, magnesium, and aluminum) readily give oxides, while platinum, silver, and gold yield metal smoke. The smoke from copper and iron consists of mixed oxides. The smoke generated in electric arc furnaces will be electrically charged, and since the initial concentration is high and is reduced comparatively slowly by the diluting air, one should expect that aggregates of wide range of complexity, electrical charge, and size would be present in arc smoke. Microscopic examination shows this to be the case, the complexes consisting of long chains, frequently of hundreds of fine particles, most of which are too small to be resolved by the optical microscope.

After the formation of particles, often an adsorbed film is formed on the surface of the particles during the process of cooling. If ample moisture (or SO_3) is present in the flue gas, it will be adsorbed on the surface of particles, thus changing the characteristics (such as resistivity) of collected particles. Adsorption of moisture is often influenced by the existence of other species. For example, a weak basic particle such as ZnO would exhibit improved adsorption capacity with the presence of HCl or H_2SO_4 vapors. Similarly, weak acidic particles such as Al_2O_3 would show improved adsorption characteristics with the presence of ammonia in the flue gas. In coal-burning furnaces, at the temperatures that exist downstream of air heaters, the SO_3 probably combines with moisture to form adsorbed H_2SO_4 on the fly ash. The H_2SO_4 is highly hygroscopic and attracts free moisture. Multiple adsorption systems of this type occur with either weak acidic (e.g. ZnO) or weak basic (As_2O_3) particles with the presence of strong acids or strong bases as just described.

Hydration and hydrolysis can also occur during the process of aging thus changing the characteristics of particles. Therefore, unless freshly collected dust particles are prevented from being directly exposed to moist gas (or ambient air), the aging of dust particles could occur, thus changing some of the particle characteristics. In the simulation of an industrial effluent, use of film adsorbed aged fine particles could result in different experimental results, for instance, if the collection efficiency of control equipment is strongly influenced by resistivity.

However, with proper handling (e.g., collection, bagging, shipping, storage, etc.) of bulk dust, it is possible to prevent or minimize the aging of fine particles for later use. The factors that we must consider are how the aging would alter the properties of particles listed in Table 1. Among the properties listed in the table, the properties which may be affected by improper handling of particles are chemical composition, moisture content, dielectric properties,

charge properties, density, size distribution, or shape. Therefore, it is of utmost importance that care be exercised from the point of source collection to the end use.

The particles in many bulk dusts and fine powders tend to clump together to a remarkable degree, and although it is possible to redisperse them, many of the airborne particles will be found to be aggregates composed of varying number of individual particles unless special precautions are taken to minimize this. However, sometimes it may be desirable to have aggregates in simulating certain industrial effluents. Since the molecular attraction becomes increasingly important as the particles become smaller, the small particles will be harder to separate than larger particles. Additional attractive force between particles may arise from surface tension effects, if vapor films are presented on the surface of particles. Powder particles dispersed in an airstream are known to carry electric charges, and in some cases electrical forces will contribute to the mutual adhesion of particles in forming aggregates. All these factors and the method of redispersion certainly would greatly influence the dispersed dust size distribution in the airstream.

5.3.2 Handling

To minimize the effect of aging as discussed in the previous section, utmost care must be exercised in the handling of fine dusts. Several steps involved in the handling of dust are:

(1) Collection -- dust must be collected on-site directly into moisture proof bags or containers with minimum exposure to atmospheric air. A high efficiency baghouse or electrostatic precipitator are the preferred dust collection methods because they maintain the original primary particle size distribution that exists in the industrial effluents.

(2) Shipping and storage -- after the collection of dust from a desired source the bagged dust should be sent to the central distribution center for storage in a humidity controlled room for added protection until it is needed.

(3) Characterization -- every batch of dust returned to the central distribution center must be characterized for needed essential information. The bag must be tagged for identification.

(4) Delivery -- upon request from user, the bags of certain dusts could be sent immediately from the distribution center warehouse.

5.4 QUALITATIVE EXPERIMENT ON FLUIDIZED BED

Dispersion of fly ash and submicron iron oxide by a simple bench-scale fluidized bed was performed in the laboratory for qualitative study of fluidized bed dispersion techniques. A schematic of the experimental set-up is shown in Figure 5. In this system fly ash or iron oxide was injected directly batchwise into the fluidized bed prior to start-up of air flow. Flyash was obtained from Dayton Power & Light Company, while submicron iron oxide was obtained from the Pfizer Company. Two types of beads (i.e. glass and nickel) both about 100 μ in diameter were used in the experiment (see Figure 6). No attempts were made to use an electrically conductive column or radioactive source for charge neutralization. However, a ground wire was provided whenever nickel beads were used for the bed.

Air flow was adjusted so that the upward air flow velocities were much less than the gravitational setting velocity of the beads in the fluidized bed. The dust had an average aerodynamic diameter at least one decade smaller than the bed solids and should have eventually elutriated out of the fluidized bed. No attempt was made to optimize the fluidized bed design at this time.

As expected, flyash was relatively easy to redisperse by fluidized bed using either glass beads or nickel beads as bed materials. The fluidized bed deagglomerated the flyash and redispersed most of it out of the bed during the first minute. There was no tendency for flyash fines to coat or attach to the glass or nickel beads.

There was visual evidence that the red iron oxides (<1 μ) remained electrostatically attached to (or coated on) the white fresh glass beads. A coating effect of iron oxides on nickel beads was not observed.

Photomicrographs of redispersed dust samples on Millipore filters are shown in Figures 7 and 8. No attempts were made to measure size distributions of the redispersed particles. With batchwise feeding of dust into bed solids, the fluidized bed could have shifted the size distribution of the dust. However, in a continuously operating dust feeder the degree of particle classification by a fluidized bed should decrease with time. Because of the nature of this project, no further experiments were performed at that time.

Qualitatively speaking, it is possible to redisperse most of the collected bulk dusts (if not all) from industrial effluents by fluidized bed. Because of the vastly different dust

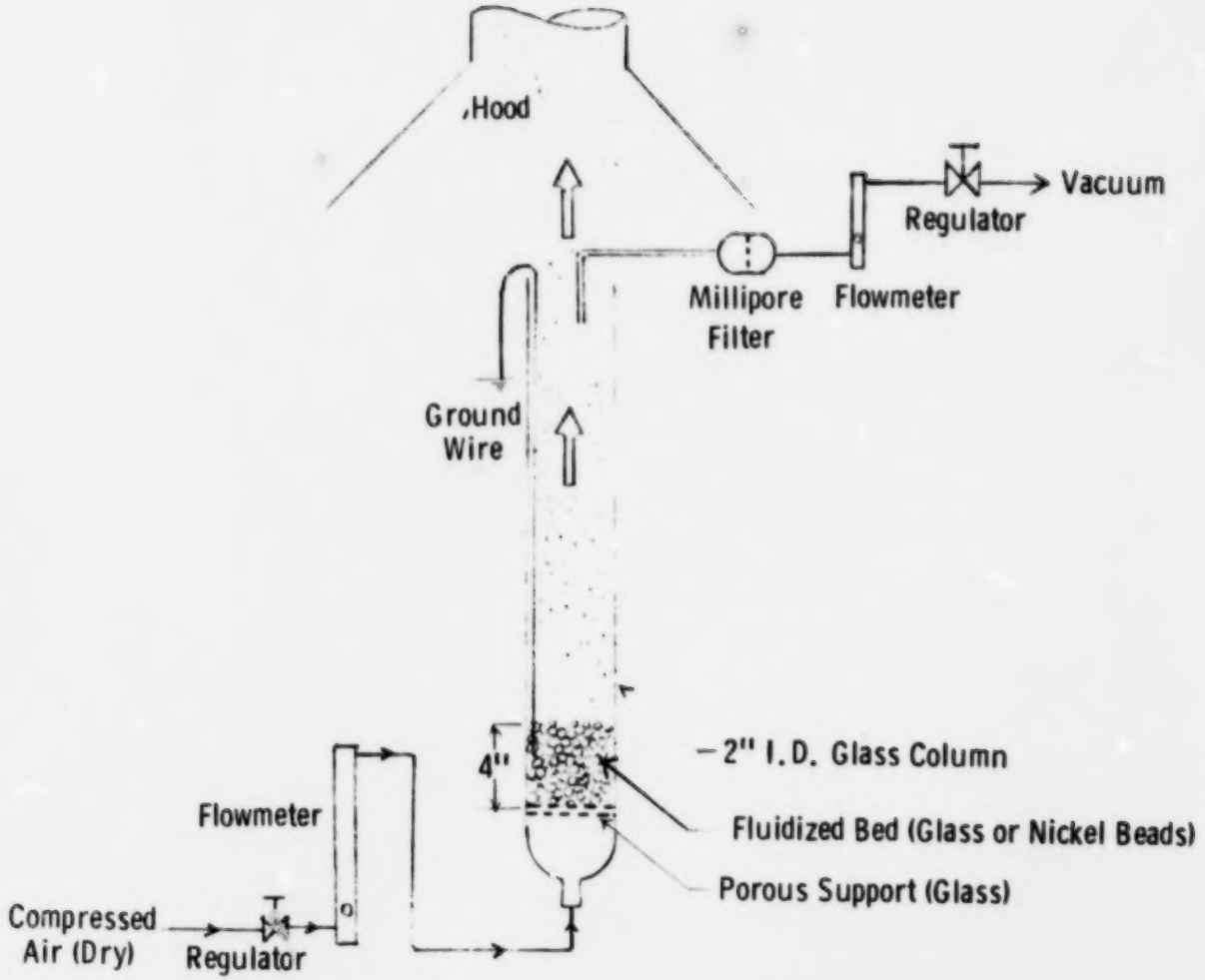
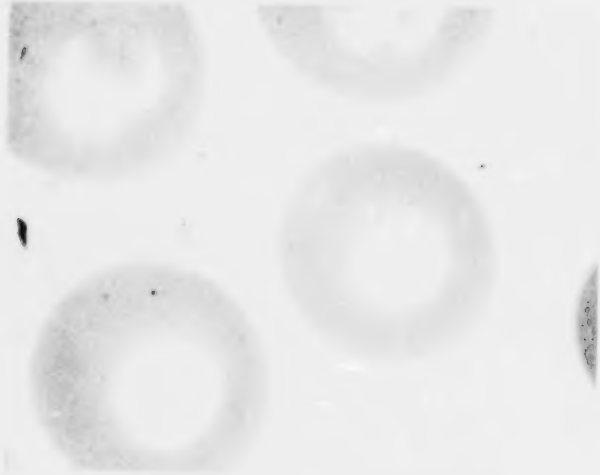
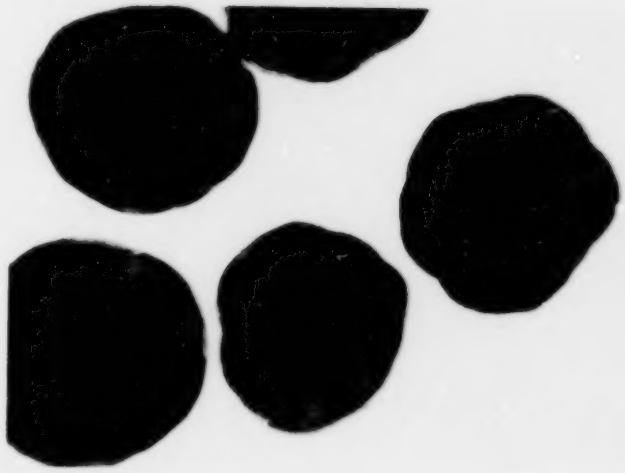


Figure 5. Schematic of Bench-Scale Fluidized Bed

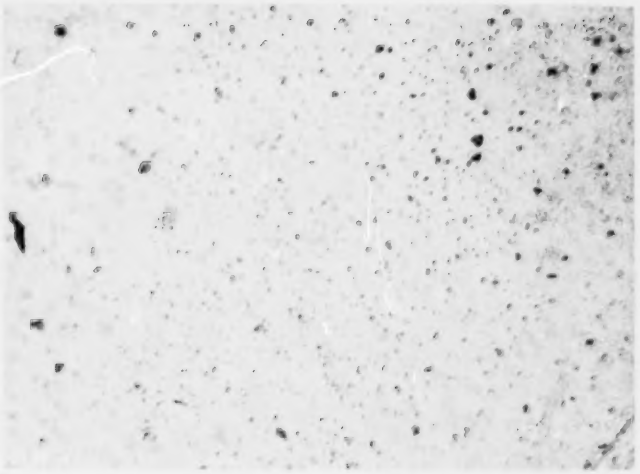


(a) Glass Beads, 225X
(Microbeads Div., Cataphote Corp.)

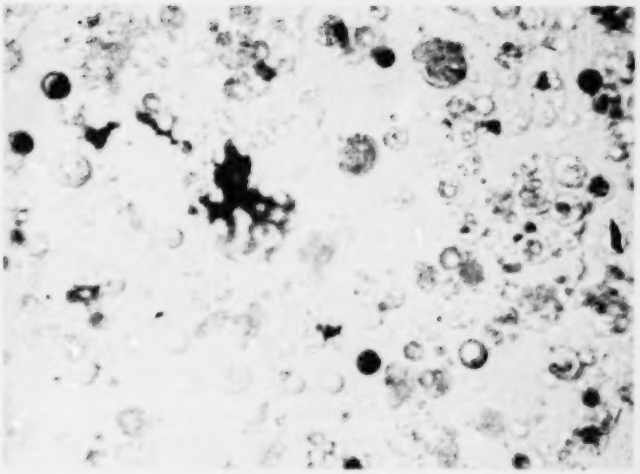


(b) Nickel Beads, 225X
(Sherritt Gorden Mines, Toronto, Canada)

Figure 6. Photomicrograph of Fluidized Bed Beads

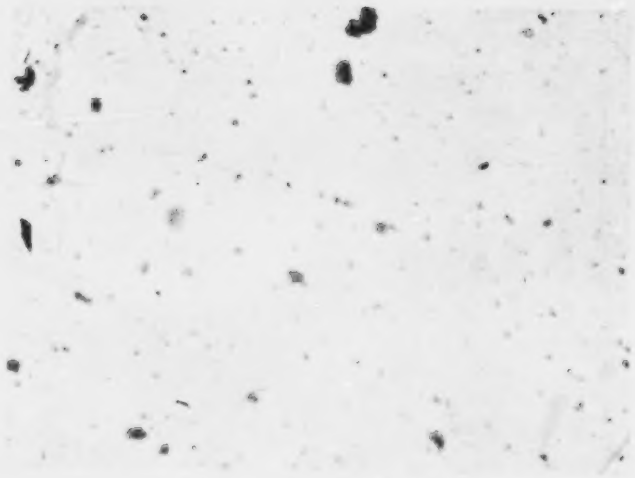


(a) Flyash, 500X

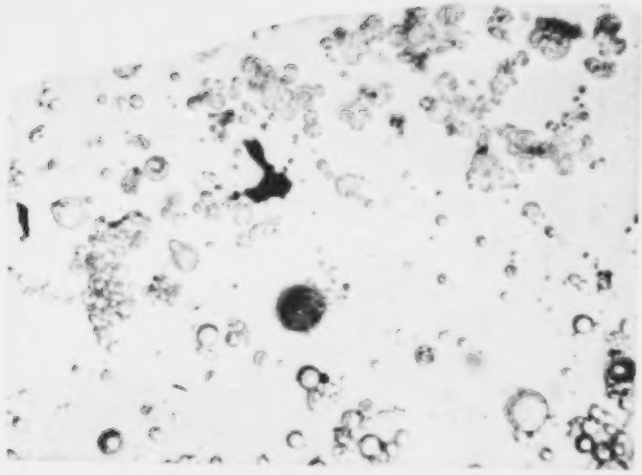


(b) Iron Oxide, 500X

Figure 7. Dispersion Using Glass Beads (~100 μ)



(a) Flyash, 500X



(b) Iron Oxide, 500X

Figure 8. Dispersion Using Nickel Beads (~100 μ)

characteristics involved, the extent of difficulty in redispersing different collected fine particles from various industries is not known at this time without further experimental investigation.

The effects of use of a radioactive charge neutralizer or use of metallic fluidized bed columns on the fluidized bed redispersion technique are also unknown. Further study on the maximum dust loading obtainable on both a bench-scale or scaled-up unit is needed.

If the fluidized bed is found to be unsuitable for redispersion of certain types of fine dust, other types of redispersion techniques (such as the jet mill) should be tested. Systematic testing and evaluation of various dust sources and redispersing techniques is thus warranted.

As mentioned previously, the characterization of a test dust under dynamic conditions can be a measure of the efficiency of redispersion of a bulk powder. A test method employed previously by us could be of interest in characterization of dispersability or aerosolizability of fine test dust. Our re-aerosolization apparatus is described in Appendix D.

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APPENDIX A

SELECTION OF DUST CHARACTERIZATION CRITERIA

Selection of criteria for the characterization of fine test dusts is based primarily on the requirements of the experiment for which the dust will be used. A test dust may be characterized to virtually any level desired. However, overclassification can become time consuming, expensive, and consequently wasteful. While all properties of a test dust are significant in characterizing a sample, a level of importance must be established for each property with regard to the mechanism by which the device being tested operates. Those properties influencing the production of the test flue gas (generated or redispersed) also require consideration in characterizing the dusts.

Six mechanisms can contribute to the particle collection efficiency of a control device: gravity, centrifugal force, inertial impaction, direct interception, diffusion, and electrostatic effects. The magnitude of the collection effect of each mechanism is generally related to particle size, with smaller particles requiring more effort and cost. The primary collection mechanisms associated with various collection devices are listed in Table 7.

Several particle properties potentially useful in characterization are: size distribution; shape, surface area, and pore volume; chemical composition; density; wettability and moisture content; solubility; hardness, abrasiveness, and grindability; charge properties; dielectric properties; corrosiveness; optical properties; and magnetic susceptibility. Although carrier gas composition and solids loading are not characteristics of fine particles, they too influence the particle properties and must be considered in the overall operation of a control device. Typical values for these properties are listed in Appendix C for the following sources; pulverized coal combustion, stoker-fired coal combustion, basic oxygen furnace, open hearth

Table 7. FORCES INFLUENCING PARTICLE COLLECTION IN AIR POLLUTION CONTROL DEVICES[5]

Class of Air Pollution Control Device	Force or Mechanism
Settling Chamber	Gravity
Cyclone	
Large Diameter	Centrifugal + Impaction
Small Diameter	Centrifugal + Impaction
Mechanical Cent. Rotor	Centrifugal + Impaction
Scrubber	
Simple Spray Tower	Impaction + Direct Interception
Packed Tower	Impaction + Direct Interception
Wet Cyclone	Impaction + Direct Interception + Centrifugal
Inertial-Power Driven	Impaction + Direct Interception + Centrifugal
Self-Induced Spray	Impaction + Direct Interception
Venturi	Impaction + Direct Interception
Filter	
High Velocity Impingement	Impaction + Direct Interception
Spun Glass Prefilters	Impaction + Direct Interception
Deep Fiber Bed	Impaction + Direct Interception + Diffusion
High Efficiency Cellulose-Asbestos or All Glass Superfine Fiber	Impaction + Direct Interception + Diffusion
Plastic Fiber-Superfine	Impaction + Direct Interception + Diffusion + Electrostatic
Cellulose Ester Membrane	Impaction + Direct Interception + Diffusion + Electrostatic
Bag or Screen Woven Fabric	Impaction + Direct Interception + Diffusion + Electrostatic
Reverse-Jet Felt	Impaction + Direct Interception + Diffusion + Electrostatic
Electrostatic Precipatator	
Single Stage High Voltage	Electrostatic
Two Stage Low Voltage	Electrostatic

*Minimum particle size collected at approximately 90% efficiency under usual operating conditions.

5. Air Pollution Manual Part II - Control Equipment, American Industrial Hygiene Association, Detroit, Michigan, 1968.

furnace, electric arc furnace, metallurgical coke ovens, cement plants, municipal incineration, iron foundries, kraft pulp mill recovery furnaces and asphalt and other crushed stone operations.

In many cases particle properties are interrelated; a change in one results in a corresponding change in others. Table 1 summarizes the relative importance of each property with respect to conventional control devices, redispersion, and size determination mechanisms. Following are discussions of each of the listed properties and their relationship to the three conventional methods of fine particle collection, redispersion, and common instrumentation types for size analysis.

A.1 SIZE DISTRIBUTION

Particle size distribution is the most important property for the characterization of a test dust. The efficiency and applicability of a particle removal technique depends to a great extent on the size of the particles to be collected. Size distribution is also of primary importance for particulate redispersion efforts and size-measuring instrumentation.

Particle size generally cannot be specified by one parameter. For irregular particles, the average dimension along three mutually perpendicular axes may be used, or the diameter of a sphere of the same volume or same surface area may be used. For extremely irregular particles other properties such as settling velocity are of more significance than actual size and shape. Some idea of the variety of shapes and sizes of primary particles in smokes is given by the electron photomicrographs shown in Figure 9.

When dealing with dust effluents from industrial sources, distinction must be made between the size and shape of primary particles and that of the aggregates formed from them. Aggregates in effluents arise from the coagulation of individual particles, and also from incomplete disintegration of powders during their dispersion. Size distribution should be determined by sampling a gas stream where the actual level of agglomeration is similar to that of the original flue gas.

A.2 SHAPE, SURFACE AREA, AND PORE VOLUME

As mentioned above, particle shape can influence the measurement of particle size. Shape and surface condition can also influence particle handling characteristics, chemical reactivity, adsorption potential, and flammability limits.

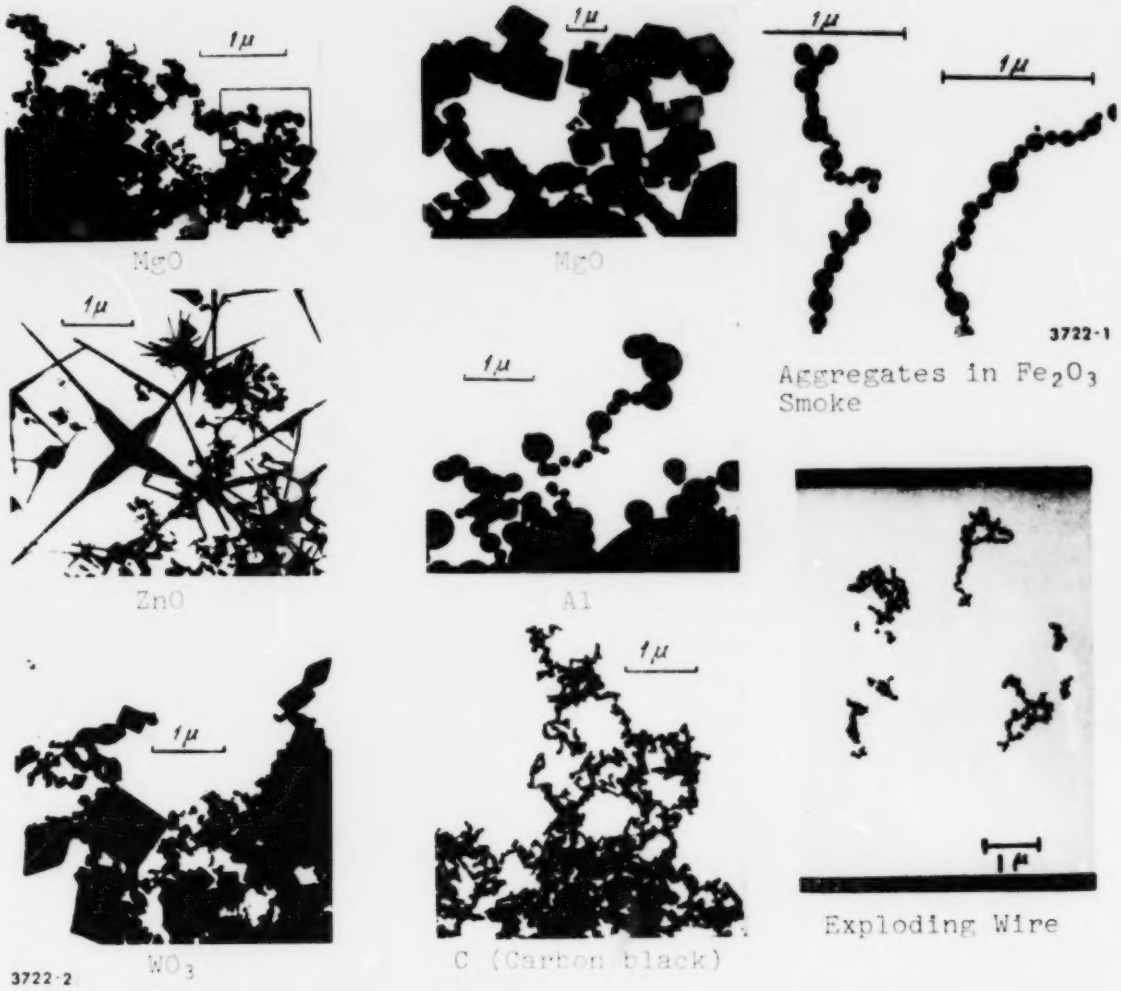

Figure 9. Electron Photomicrographs of Aerosol Particles in Smokes

As particle size is reduced, surface properties predominate over bulk properties in controlling the physical and chemical behavior of finely divided solids. As a consequence, the surface area and distribution of pore sizes becomes of utmost importance owing to the exaggerated tendencies for adsorption of gases and moisture, and the extent to which the particle can be electrically charged by triboelectric phenomena.

Shape is of secondary importance for high energy wet scrubbing, electrostatic precipitation, and redispersion, while it is of primary importance for fabric filtration where the shape of the collected particles is critical to the cleaning cycle of the filter operation. Fine needle-shaped particles have a tendency to remain trapped in the filter fabric during the cleaning cycle, thereby plugging the filter and reducing its operating efficiency.

Shape, surface area, and pore volume area of varied importance to the operation of different types of particle sizing equipment. The orientation of irregularly shaped particles is of primary importance to the size distribution obtained from an optical measuring device. Surface area, as it influences a particle's ability to be charged, is very important to electrical size measuring equipment utilizing a particle charging mechanism. For mechanical and physico-chemical size analyzers, shape, surface area, and pore volume are only of secondary importance. The shape of a particle can influence its aerodynamic behavior in a mechanical sizing instrument, while the surface properties of a particle may either aid or hinder vapor condensation on particles in a physico-chemical sizing technique.

A.3 CHEMICAL COMPOSITION

The chemical composition of a dust particle is a very reliable method of characterizing the dust and identifying its origin, but the mechanisms of particle collection are physical and electrostatic in nature, not chemial. Consequently, chemical composition is only important to the extent that it influences the physical and electrical properties of the dust particle. The same is true for size measuring techniques. The mechanisms are based on physical properties of the particles, not chemical, but the chemical composition of the particle is a prime factor in determining what the important physical properties are.

A.4 DENSITY

Both bulk and real particle density are of primary importance for handling and collection of fine dusts. The

effort required to redisperse collected dusts will be influenced by the particle density. Once dispersed, density plays an important role in the collection mechanisms of impaction, direct interception, and diffusion, all of which are important to the three collection devices being considered.

Mechanical, optical, and thermal size measurement techniques all utilize inertial impaction. Consequently, particle density is important for their operation. For mechanical devices, density is more important than for electrical or thermal devices because inertial impaction is the primary sizing mechanism. The effective density of the particles is utilized for size classification by accelerating the particles (e.g., centrifugally or through an orifice), while for the other two types of device, inertia acts only as an assist to the electrical or thermal force exerted on the particle.

A.5 WETTABILITY AND MOISTURE CONTENT

Moisture content is the result of the wettability of a particle. Wettability, in turn, depends on the nature of the dust particle, and is related to boundary surface energies. Wetting occurs when solid/liquid adhesion energy exceeds liquid cohesion energy.

This phenomenon can affect particle collection in wet scrubbers, although it is generally only a second-order effect. The collection efficiency may be improved by the increased particle size resulting from moisture collection on the particle surface.

Moisture in dust particles will contribute to increased agglomeration of particles collected for redispersion, adding potential difficulties to the redispersion operation. Once dispersed, a dust of high moisture content will have a tendency to cake on the collection surface, thus inhibiting further collection. Moisture content also exerts a strong influence on the particle resistivity, flammability, and handling characteristics.

Wettability is of prime importance for particle sizing via physico-chemical techniques. For example, the operation of a nuclei condensation particle sizing instrument is based on the condensation of water vapor on fine particles, enlarging their size for ease of observation. Should a particle not be wettable, e.g. DOP particles, this type of size measuring device will not be applicable.

A.6 SOLUBILITY

Solubility of fine particles in water is of secondary importance for conventional fine particulate collection devices. For wet collection devices, solubility is of most concern with regard to operating conditions, i.e., recycle ratio. Another possible influence of particle solubility on wet collection is a change in the collection efficiency due to soluble components of collected particulate in the recycle liquor. Dry collection devices can be adversely affected by solubilized particulate. Soluble particulate components can accelerate equipment failure by corroding collection surfaces of an electrostatic precipitator or by contributing to bag failure in a fabric filter.

A.7 HARDNESS, ABRASIVENESS, AND GRINDABILITY

These three properties are not related to any collection mechanism and consequently are not of primary importance. However, they are of importance with respect to equipment lifetime and selection of materials of construction. Of the conventional collection devices, fabric filters are most susceptible to deterioration and failure from continuous bombardment by abrasive particles.

Another area in which hardness, abrasiveness, and grindability play an important role is in the production of a test flue gas. To redisperse a collected dust sample requires an input of energy. Supplying adequate energy for redispersal may also provide enough energy to break the particles, yielding an aerosol of different size distribution from the original flue gas.

A.8 CHARGE PROPERTIES

Most industrial dusts are charged to an appreciable extent, but the fractions of positively and negatively charged particles are similar so that an overall flue gas is generally neutral. Mechanisms that contribute to the charging of dusts include electrolytic mechanisms, contact potential, spray electrification, contact separation, ion diffusion, and electric field charging processes in gases. The controlling factor limiting the level of charging of solid particles is the surface area of the particle, while for liquid droplets the controlling factors are size and surface tension. The electrostatic characteristics of the charged particles are utilized to facilitate collection. Both the primary particle capture and consequent collection are enhanced by electrostatic attraction.

The ability of a particle to become charged is of secondary importance for conventional particle collection equipment. For electrostatic precipitators particles must be able to be charged for collection but the ability to drain that charge is more critical. Collection efficiencies for both wet scrubbers and fabric filters may be enhanced by both natural and induced particle charging. The charge properties of particulates play an important role in redispersion attempts. Charged particles tend to agglomerate when redispersion is attempted, and when fluidized bed dispersion techniques are used, charged particles tend to adhere to the bed material.

Both electrical and mechanical size measuring techniques are influenced by particle charge properties. The primary importance of charge properties on electrical sizing equipment is self explanatory; the mechanism by which an electrical particle sizing device operates depends on the force exerted on charged particles in an electric field. Mechanical sizing equipment operation can be adversely affected by charged particles. In devices where particles have a tendency to become charged (e.g., cascade impactor where high speeds and particle collisions occur), collection efficiency may be hampered by collection surfaces becoming charged and subsequently repelling particles. Particle charging characteristics are important to the study of fine particle behavior and collection.

A.9 DIELECTRIC PROPERTIES

Of more critical importance is the capability of the particles to conduct electricity and drain their charge once collected. If the charge cannot be drained, an electrostatic barrier to further particle deposition may form. For normal electrostatic precipitation a maximum resistivity of 2×10^{10} ohm-cm (measured *in situ*) is required.[6] There are a number of factors that influence the apparent resistivity of particulates. Some of the important factors are particle size distribution and shape, temperature, surface energy characteristics, packing configuration, and chemical composition. The resistivity is also a function of carrier gas temperature and composition.

The electrical resistivity of a bulk layer of particles depends on both surface and volume factors. Below 300-350°F surface conductivity predominates, with electrical charges being conducted along the particle surface through adsorbed

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6. Vandergrift, A. E., et al., "Particulate Pollutant System Study," Vol. III: Handbook of Emission Properties, Midwest Research Institute, 1 May 1971, PB 203 522.

chemical films. At higher temperatures volume conduction due to temperature excitation of internal electrons predominates.

While size measuring techniques are similarly affected by both charge and dielectric properties, dielectric properties are more important with regard to particle collection mechanisms. The ability to drain charge is important to all particle collection equipment but is of primary importance for dry collection mechanisms. Particle charge enhances collection, but if the charge is not easily drained from the particle on the collection surface of either an electrostatis precipitator or fabric filter, an electrostatic barrier to further particle collection may form.

A.10 CORROSIVENESS

Corrosiveness is of primary importance for wet scrubbers, and only of secondary importance for dry collectors. This is due to the fact that in dry collectors the solid/solid contact between a corrosive material and the collection surface is not as intimate as it is in the solutions formed in wet scrubbers. Also, corrosiveness is primarily due to carrier gas components (for the industries of interest) with particle composition contributing a minor effect. The potential corrosive nature of a wet slurry must be considered in the selection of appropriate materials of construction.

However, if the carrier gas has high moisture content, corrosive compounds adsorbed on the particle surface may come into close contact with the collection surfaces of dry collectors, producing a corrosive effect, reducing precipitator life, or contributing to bag failure in a fabric filter. Corrosiveness is a minimal problem for redispersion efforts since dusts are generally kept dry to inhibit agglomeration.

Corrosiveness will have minimal effect on most sizing instruments. However, the corrosive nature of particulate could be enhanced in physico-chemical measuring equipment due to the high moisture content required by nuclei condensation devices to enlarge the particles by condensation.

A.11 OPTICAL PROPERTIES

Optical properties are of interest primarily in particle sizing instrumentation. Photophoresis is the force imparted to fine particles when exposed to illumination. The photophoretic velocity at illumination of an intensity comparable to sunlight at sea level is of the order of 10^{-2} cm/sec.[7]

Optical instruments may utilize either the transmission or the scattering of light to determine either the concentration or particle size of an aerosol. The particle refractive index is very important in the determination of particle size using light scattering techniques. As can be seen in Figure 10 the refractive index of a particle can influence the apparent size measurement for fine particles and introduce a significant error in size determination efforts. Physico-chemical sizing techniques are somewhat influenced by optical properties due to the use of optical techniques after the particles have been enlarged by vapor condensation on the particle surface.

A.12 MAGNETIC PROPERTIES

Magnetic susceptibility may indirectly influence particle collection efficiency by enhancing the tendency for magnetic particles to agglomerate, increasing their size and improving collection efficiency. The use of magnetophoretic mechanisms for novel particulate collection equipment has also been suggested.

Any increased tendency toward agglomeration will be critical with regard to redispersion of collected dusts. The force required to break an aggregate in which there are magnetic forces between particles is 100-1000 times greater than for an aggregate held together by only molecular forces.[8]

The use of magnetic susceptibility in instrumentation as a method for size classification is of limited applicability. Studies of the effect of particle size on

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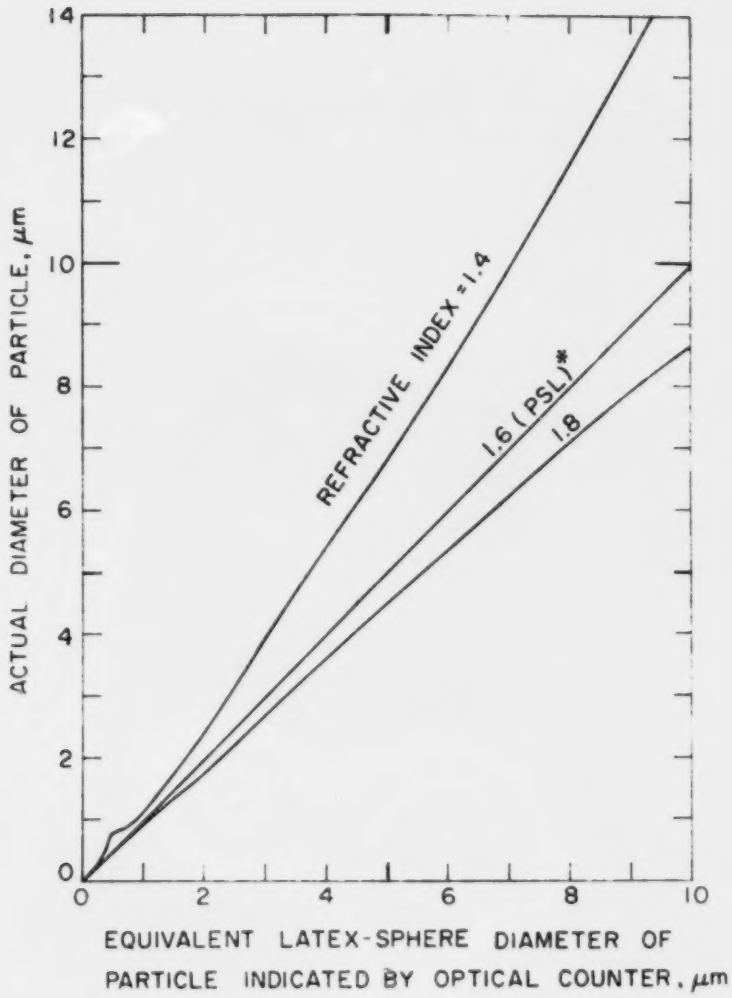
7. Davies, C. N., Aerosol Science, Academic Press, Inc., New York, N.Y., 1966.

8. Fuchs, N. A., The Mechanics of Aerosols, Pergamon Press, New York, N.Y., 1964.



*Polystyrene Latex

Figure 10. Calculated Effect of Particle Refractive Index on the Calibration of the Optical Counter[9]

9. Whitby, K. T., Liu, B. Y. H., Husar, R. B., and Barsic, N. J., "The Minnesota Aerosol-Analyzing System Used in the Los Angeles Smog Project," Journal of Colloid and Interface Science, 39(1), 136-64 (1974).

magnetic susceptibility have shown a direct relationship for some materials (e.g., graphite), but in general the magnetic susceptibility of powdered metals is independent of particle size.[10,11]

A.13 CARRIER GAS COMPOSITION AND SOLIDS LOADING

These two items are not properties used to characterize test dusts, but they are both of concern for the testing of fine particle control devices.

The carrier gas composition is of interest mainly as it affects the physical characteristics of the particles. For example, allowing sufficient contact time, the humidity of the carrier gas is directly related to the moisture content of the dust particles. The moisture content and other adsorbed species, especially SO_3, also affect the electrical properties and handling characteristics. Finally, components of the carrier gas may be corrosive in nature and contribute to the corrosiveness of a wet scrubber slurry.

Although solids loading is not a particle property it is essential in the selection of a control device or system. Solids loading is of particular interest for redispersal of collected dusts with regard to the capacity required for the redispersal unit.

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10. Irani, R. R. and Callis, C. F., Particle Size: Measurement Interpretation, and Application, John Wiley and Sons, Inc., New York, N.Y., 1956.

11. Selwood, P. W., Magnetochemistry, second edition, Interscience Publishers, New York, N.Y., 1956.

APPENDIX B

DUST CHARACTERIZATION TECHNIQUES

The following is a discussion of potential methods for characterizing test dusts. Techniques for obtaining values for the properties discussed in Appendix A are presented.

B.1 PARTICLE SIZE DISTRIBUTION

Particle size is of great importance for the characterization of test dusts since size is usually the characteristic that most markedly affects the behavior of particulate materials. The need for characterization of the particle size distribution of test dusts could occur in two alternate stages of use:

a. Laboratory analysis for primary particle size distribution

b. Size distribution for aerosolized (or stack) conditions

Characterization in the first case is addressed to obtaining information concerning the size distribution of the bulk test powder. This laboratory measurement yields information on the size distribution of primary particles. Characterization in the second case will define the test dust behavior under dynamic test conditions, i.e., a measure of the efficiency of redispersion of the bulk powder and the extent of agglomeration or aggregation of the primary particles. This analysis must be performed on aerosolized dust, preferably at the test facility using the actual test flue gas. For simulation of industrial sources the actual size distribution is of secondary importance compared to whether the size distribution is similar to that which exists in the actual industrial

effluent. This comparison requires previous knowledge of particle size distribution in the actual industrial effluent.

B.1.1 Particle Sizing Techniques

Davies[12,13,14] has recently presented a detailed review of the physical principles employed to sense and size particles. This review was directed to rapid response instrumentation for particle size analysis and listed the following particle sensing concepts:

1. Image replication
2. Electrical resistance charge
3. Light scattering
4. Light obscuration
5. β-ray attenuation
6. X-ray absorption
7. Acoustic interference
8. Ultrasonic attenuation
9. Differential flow classification
10. Pulsating gas flow
11. Pressure drop in nozzles
12. Transient and evaporative cooling of a hot wire
13. Impact and momentum measurement
14. Magnetic flux variations
15. Electrostatic ion capture

A four-volume publication by G. J. Sem et al.[15,16,17,18] discusses the state of the art of instrumentation for the measurement of particulate emissions from combustion sources. A summary of types of size analysis techniques appears in Table 8.

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12. Davies, R., "Rapid Response Instrumentation for Particle Size Analyzer - A Review," Part I. American Laboratory, p. 17-23, December 1973.
13. Davies, R., ibid, Part II, January 1974, pp 72-86.
14. Davies, R., ibid, Part III, February 1974, pp 47-55.
15. Sem, G. J., et al., Thermo-Systems, Inc., "State-of-the-Art: 1971 Instrumentation for Measurement of Particulate Emissions from Combustion Sources, Vol I, April 1971.
16. Sem, G. J., ibid, Vol II.
17. Sem, G. J., ibid, Vol III.
18. Sem, G. J., ibid, Vol IV.

Table 8. SUMMARY OF TYPES OF SIZE-ANALYSIS TECHNIQUES[19]

Size-discriminating Property		Technique and Variations			Range of Applicable Particle Diameter,* microns
Type	Character or Mechanism				
Geometric	Physical barrier	Sieving	Wet		5-1000
			Dry		
		Ultrafiltration			0.01-5
Mechanical or Dynamic (in fluids)	Inertia	Impaction on surface			0.1-100
		Pressure pulse (sonic)			10-1000(?)
	Terminal settling velocity (in gravity or centrifugal fields) (possibilities of using electrical fields exist)	Elutriation	Single fractionation	Liquid	5-100
				Gas	
			Series fractionation	Liquid	
				Gas	
		Sedimentation	Layer methods (differential)	Liquid	1-100(G) 0.02-10(C) 0.002-1(UC)
				Gas	
			Suspension methods	Differential-liquid	
				Integral-liquid	
				Integral-gas	
		Decantation (in liquid only)			1-100(G)
		Photo-sedimentation (photography of particle streaks)			1-100(G)
	Diffusion	Particle displacement (random walk)			0.01-1
		Particle deposition			
Optical	Imaging†	Light microscopy			0.2-100
		Ultramicroscopy (gives mean size only)			0.005-1
		Electron microscopy			0.002-15
	Transmission (spectral)	Extinction measured as function of wavelength			0.1-2(?)
	Scattering	Single particle count	Right angle (90°)		0.2-50 (higher with microwave)
			Angular		
			Forward		
			Polarization		
		Macroscopic (gives mean size only)			
	Diffraction	Light			
		X-ray			
		Laser (holography-reconstruction of diffraction pattern)			
Electrical	Resistance	Alteration of current flow by particles			1-100
	Capacitance	Potential pulse due to particle deposition			
	Charge	Tribo-charging			1-30
		Induction charging			
		Corona charging			
Magnetic	Applicable to magnetic materials only	Particle migration in magnetic fields, magnetic pulses			
Thermal	Particle deposition	Particle migration in thermal gradient			0.1-10(?)
Physico-chemical	Condensation	Growth of nuclei with controlled supersaturation			0.01-0.1(?)

* Items in parentheses have following significance: C—in centrifugal field; G—in gravity field; UC—ultracentrifuge.

† Replicas may be used in place of particles that might evaporate or be destroyed during measurement, e.g., in electron microscopy to avoid the effect of vacuum or electron beams, and in magnesium oxide fume method for measuring size of drops.

19. Lapple, C. E., "Particle-Size Analysis and Analyzers," Chemical Engineering 75, 149-156 (1968).

Table 8 shows that the equipment required depends on the size range of the dust particles. For simulation of industrial sources it is apparent that the wide range of sizes present from different sources and within each source (See Appendix C) would necessitate the use of multiple pieces of sizing equipment.

B.1.2 Primary Particle Sizing

The primary particle size distribution can be obtained in the laboratory using a sample of collected dust. The most common method for this type of measurement is microscopy. For optical microscopy the size-limiting factor ($\sim$0.5 μ) is controlled by the wavelength of the light used. As the particle size approaches the wavelength of light used, the particle cannot be resolved. Smaller particles can, however, be detected using electron microscopy.

In both cases counting aids may be used to facilitate size distribution determination. A mechanical aid, shown in Figure 11, has been designed by MRC for simple size distribution calculations using negatives obtained by microscopic techniques.[20] The images of the particles are projected down upon tracing paper by a spot projector located above the table using one of several calibrated-diameter beams of light. The sizes of the projected beam of light are matched to the projected particle through the paper. When the size of the projected spot matches that of the particle, a foot switch is pressed to record the particle size in a bank of counters. Another method for speeding the counting operation is to incorporate automatic computer counting with the microscopic detection instrument, for example, scanning electron micrograph.

Microscopy is an ultimate size measuring technique where the actual physical size of the particle is the parameter measured. Because of this direct observation, microscopic size determination is frequently used as a primary standard for the calibration of other sizing equipment.

Unfortunately, microscopy has disadvantages for generating a particle size distribution. The primary disadvantage is the time required to obtain results. Microscopy is not a real-time particle sizing technique, and preparation of a sample for analysis is an extensive and tedious operation.

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20. Hedley, W. H., et al., "Studies of the Surface Chemistry of Solids in Dissemination," Final Report, Contract DAA15-68-C-0006, U.S. Army, Edgewood Arsenal, 1969.

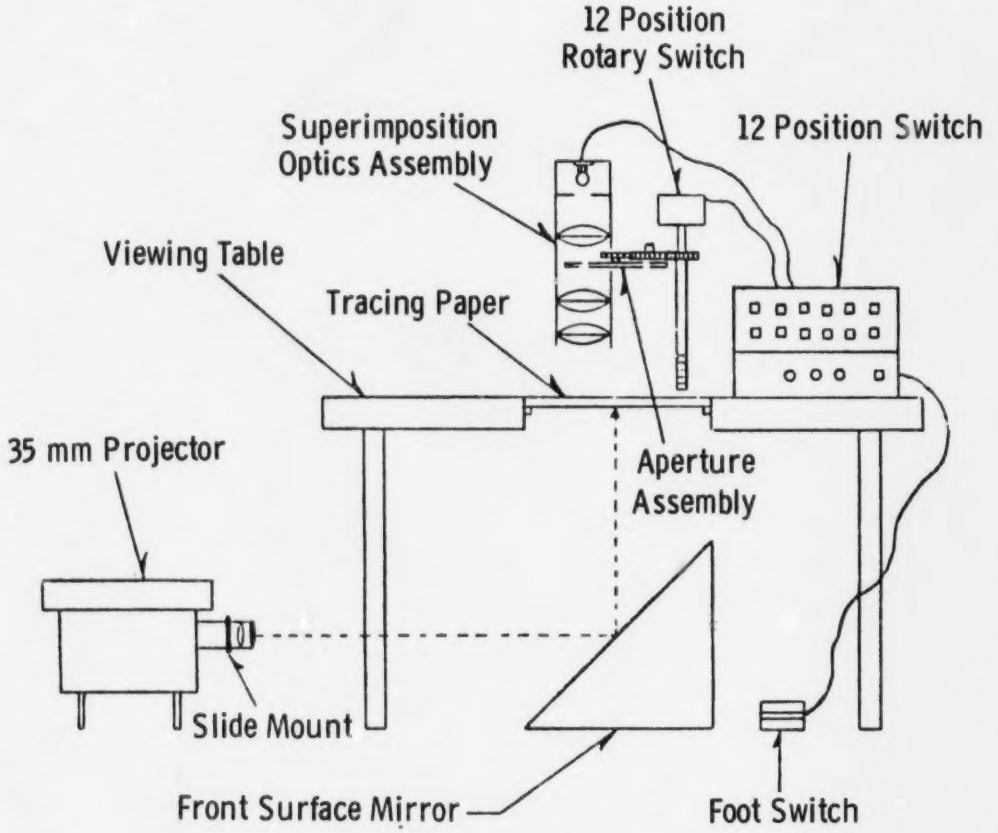

Figure 11. Schematic Diagram of Particle Size Comparator

B.1.3 Aerosolized-Size-Distribution

Potential combinations of sensing and sizing equipment which appear to be technically feasible and which also appear to be most practical for application to effluent testing are listed in Table 9. Not all combinations in Table 9 are equally applicable, however, and most combinations have not yet been developed.

Figures 12 and 13 present potential combinations of equipment for determining the size distribution of fine particulates on a continuous basis.

To reduce the concentration of particles to within the limits of the sensing equipment, flue gas dilution capability is required. The dilution chamber also prevents condensation of moisture in the flue gas, which could change particle size or damage equipment.

Photoelectric or optical particle counters function on the principle of light scattering; that is, each particle in a continuous flowing stream passing through a beam of light scatters light onto a phototube during the time the particle is illuminated. The amount of scattered light is proportional to the square of the diameter of the particle. The overall system is usually calibrated in terms of particles per unit volume of unit size. A count is indicated for all particles passing through the instrument whose sizes are larger than a selectable preset minimum. The photoelectric particle counter will give reliable size distribution information up to concentrations of ~1000 particles per cubic centimeter. Above this concentration limit, the frequency of occurrence of more than one particle in the view volume of the photometer will affect the measured size distribution; these particles will be counted as a single larger particle. This range can be extended with an internal dilution system. This type of equipment is applicable for particles from 0.2 μ to the cyclone cut point of 10 μ.

Condensation nuclei counters function on the ability of particles to act as centers (nuclei) for the condensation of water vapor in a supersaturated environment. The technique is used for particle measurements in the 0.002 to 0.3 micron range. The concentration of the grown particles is then measured by attenuation or scattering of light. Particles in this size range are frequently referred to as condensation or Aitken nuclei. In condensation nuclei detectors, a sample is withdrawn from the aerosol stream, humidified, and brought to a supersaturated condition. In this supersaturated condition, condensation

Table 9. OPERABLE SIZE RANGES OF PRACTICAL COMBINATIONS OF SIZE CLASSIFIERS AND SENSORS

All numbers are the diameter, in microns, of a spherical particle with a density of 1.0 g/cu cm[13]

PARTICLE SIZE CLASSIFIER		CONCENTRATION SENSING TECHNIQUE						
		MASS		OPTICAL				
		BETA RADIATION ATTENUATION 0.01 - 100	PIEZOELECTRIC QUARTZ CRYSTAL 0.01 - 20	LIGHT TRANSMISSION 0.2 - 100	PHOTOMETRY 0.2 -50	SOILING POTENTIAL 0.2 - 50	ELECTROSTATIC ION CAPTURE AND ATTENUATION 0.005-100	NUCLEI COUNTER 0.001 - 0.05
AERODYNAMIC	IMPACTOR 0.2**- 30	0.2* - 30	0.2* -20	0.2 — 30	0.2 — 30	0.2 — 30	0.2 — 30	-
AERODYNAMIC	CYCLONE 0.5 - 30	0.5* - 30	0.5* -20	0.5 — 30	0.5 — 30	0.5 — 30	0.5 — 30	-
AERODYNAMIC	GRAVITATIONAL ELUTRIATOR 1.0 - 100	1.0* -100	1.0* -20	1.0 — 100	1.0 — 50	1.0 — 50	1.0 — 100	-
AERODYNAMIC	GRAVITATIONAL SEDIMENTATION 1.0 - 50	1.0* -50	1.0* -20	1.0 — 50	1.0 — 50	1.0 — 50	1.0 — 50	-
	ELECTROSTATIC 0.005 - 0.6	-	-	-	-	-	0.005 — 0.6	0.005 — 0.05
	BROWNIAN DIFFUSION 0.001 - 0.05	-	-	-	-	-	-	0.001 — 0.05

*Although this is the lowest size cutoff of the classifier, the sensor can detect smaller particles below this size cutoff, lumping them into one size range.

**Low pressure impactor may prove useful down to 0.05 microns for some applications where volatile particles are not present.

13. Sem, G. J., ibid, Vol. III.

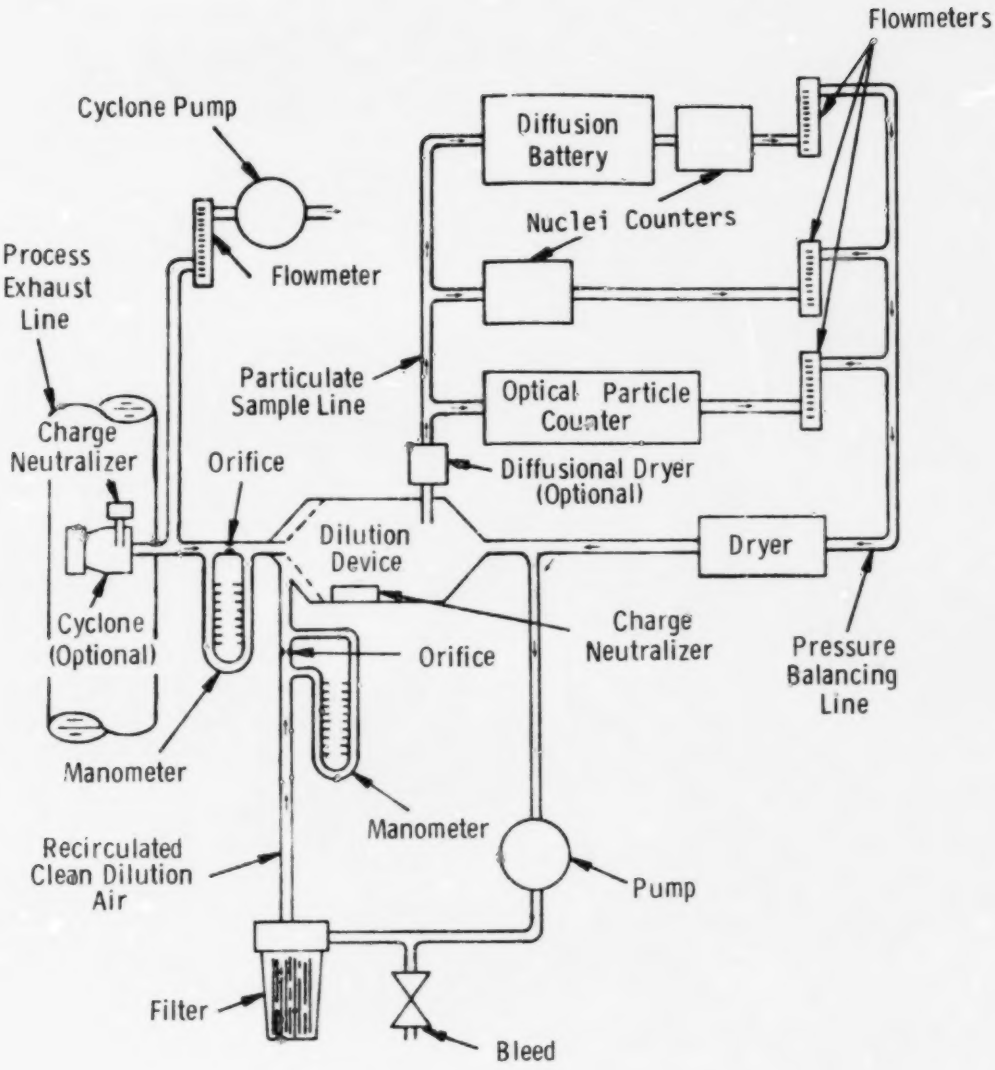

Figure 12. Schematic of Potential Particle Size Distribution Measurement System Utilizing a Diffusion Battery

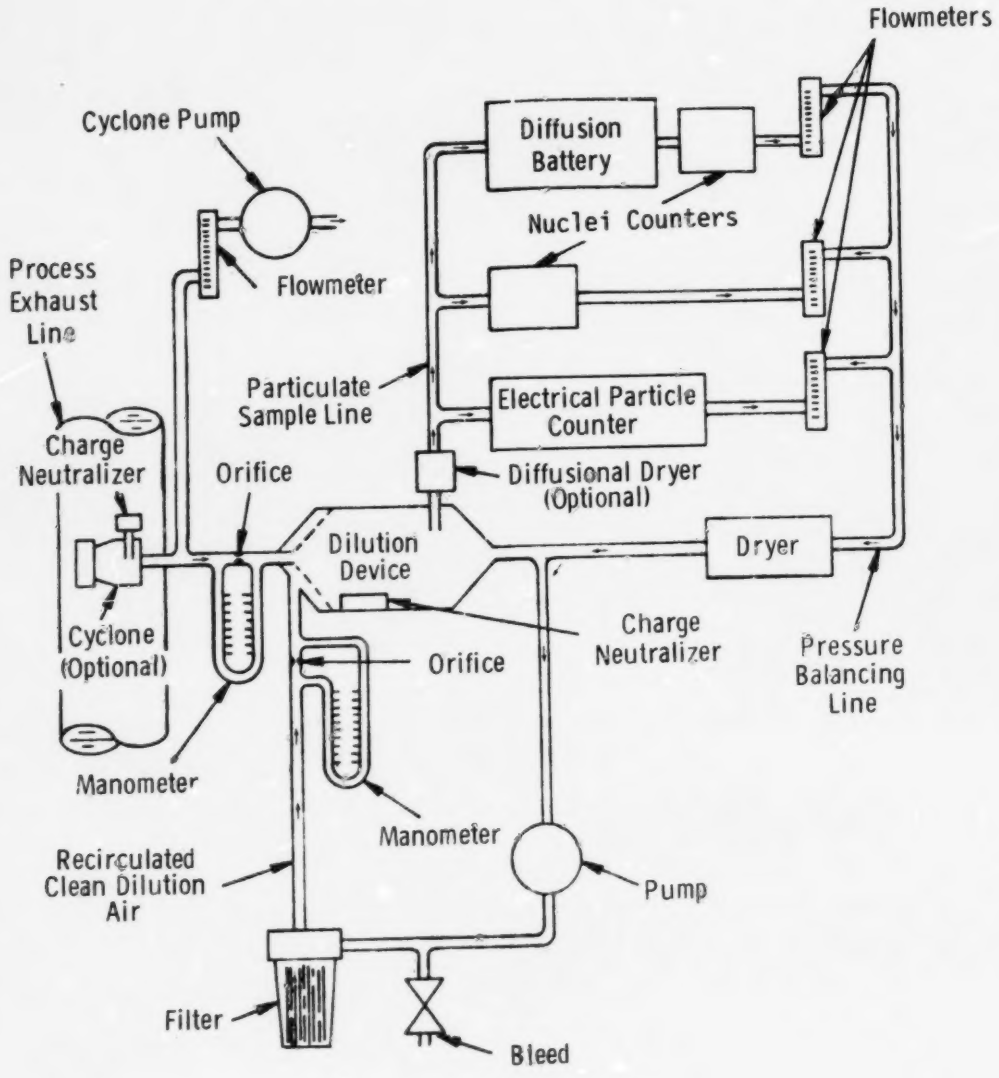

Figure 13. Schematic of Potential Particle Size Distribution Measurement System Utilizing an Electrical Particle Counter

will be initiated on all particles larger than a certain critical size and will continue as long as the sample is supersaturated. This condensation process forms a homogeneous aerosol, predominantly composed of water, containing one water drop for each original particle (condensation nucleus) whose size was greater than the critical size appropriate to the supersaturation obtained. Greater supersaturation is used to initiate growth on smaller particles. The number of grown particles is determined from the characteristic optical properties of the final, grown aerosol, with the scattered light method described earlier being commonly used.

A diffusion battery consists of a number of long, narrow, channels, an example unit being about 20 parallel channels, 0.1 mm wide, 10-12 cm high and 10 cm or more long whose dimensions are adjusted to permit variations in length and spacing as a means of particle size measurement in a selected size range. Gravity and particle density have a negligible effect on particles below a diameter of 0.6 micron. As the aerosol moves in streamline flow through the long narrow rectangular channels, the random Brownian movement of the particles causes them to displace from their original position in the air flow streamline. The most probable displacement from a streamline is zero, but the average displacement is proportional to the square root of the travel time. Consequently, some of the particles are displaced sufficiently to reach the wall of the battery. It is assumed that once the particle reaches the battery wall, it will adhere. Therefore, a fraction F of the influent particles appear in the battery effluent. Since the magnitude of the Brownian movement increases with decreasing particle size, the smaller the particle size, the lower the value of F. From the value of F, the diffusion constant D of the aerosol may be obtained and the particle size calculated.

By selecting one of a series of sizes of diffusion batteries all particles less than a selected minimum size can be measured. The percent penetration of particles through the diffusion battery (particle concentration in divided by particle concentration out) is determined from particle concentration measurements made using a condensation nuclei counter described earlier.[21]

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21. Gellman, I., "Methods and Experience in the Measurement of Submicron Particles in Source Emissions and the Ambient Air," Atmospheric Quality Improvement Technical Bulletin No. 62, National Council of the Paper Industry for Air and Stream Improvement, New York, N.Y., August 1972.

Another potential sizing train replaces the diffusion battery with an electrical particle counter. The sizing range of an electrical particle counter is 0.005 to 0.6 μ. It operates on the principle that distinctly different charges can be imposed on different sized aerosols and the mobility of these particles differs and can be measured. A combination optical counter, electrical, and nuclei counter has been used by University of Minnesota personnel to determine the number size distribution of an aerosol from 0.002 to 10 μ (Figure 14.) The time for a measurement cycle is about four minutes.

Numerous other alternatives are available, each having advantages and disadvantages. However, the systems used at any specific laboratory facility are usually based on the available equipment at that location to minimize capital expenditure and labor.

B.2 SHAPE, SURFACE AREA, AND PORE VOLUME

H. Green [22] and G. Martin, et al [23] have shown that for irregularly shaped particles of a material having a statistical diameter d_s and a volume V, V/d_s^3 is constant. The various particles of a sample to which d_s applies will possess different individual volumes but the total volume of all the individual particles for any distribution of particles having the same average diameter will be constant. If the particles are individual spheres of different sizes, the value of the constant will be $\pi/6$ (e.g., $V = \pi/6\ d^3$).

However, for irregularly sized particles, the value of this constant is less than $\pi/6$. This reasoning may also be extended to surfaces, so that if S is the aggregate surface area of a group of particles possessing an average diameter d_s, then S/d_s is constant. The value of this constant for spheres of different sizes would be π (e.g., $S = \pi d^3$), while the value of the constant for irregular particles would be less than π. If the volume constant is denoted by α_v, and the surface constant by α_s, then:

$$V = \alpha_v d_s^3 \qquad S = \alpha_s d_s^2.$$

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22. Green, H., "The Effect of Non-Uniformity and Particle Shape on Average Particle Size," Journal of the Franklin Institute, 204, 713-29 (1927).

23. Martin, G., et al., "Researches on the Theory of Fine Grinding, Law Governing the Connection Between the Number of Particles and their Diameters in Grinding Crushed Sand," Transactions British Ceramic Society, 23, 61-109 (1923).

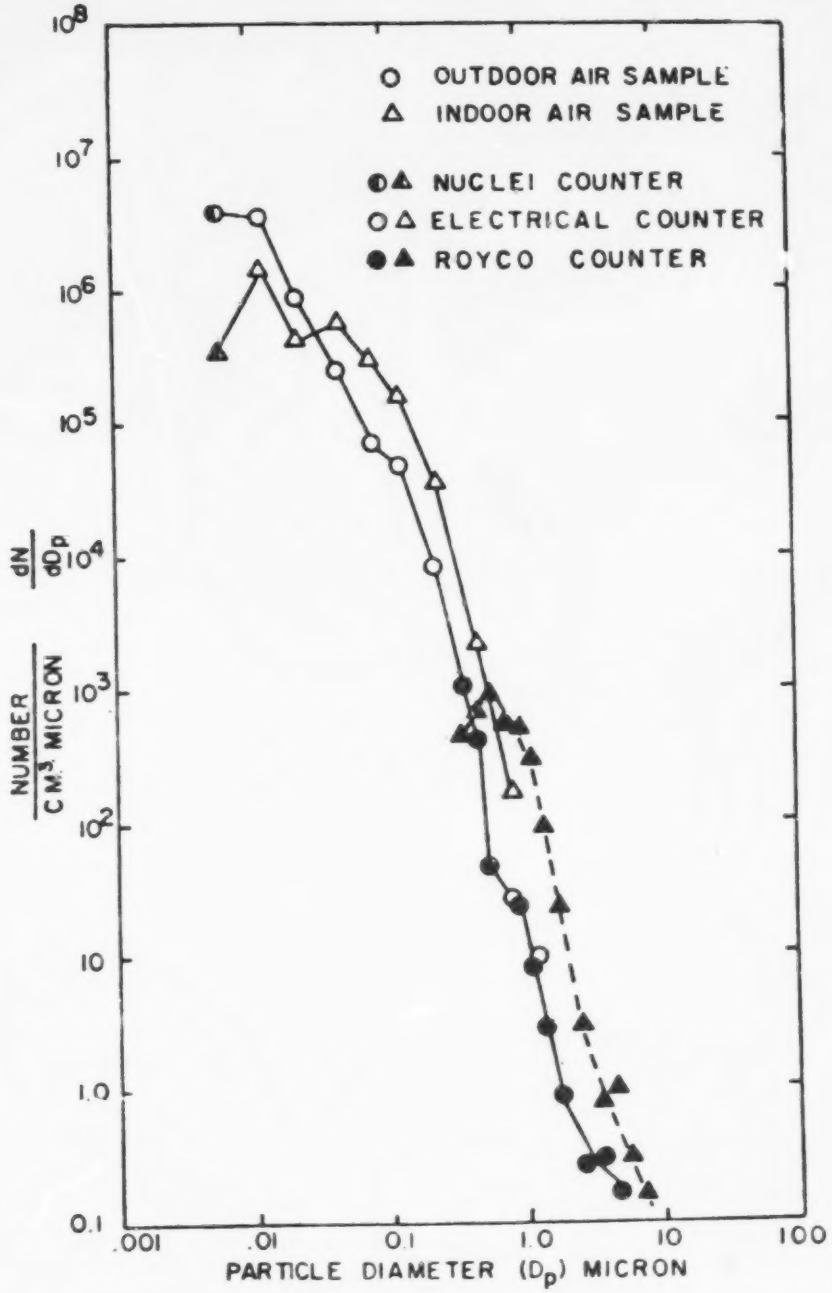

Figure 14. Size Distributions of Indoor and Outdoor Aerosols[24]

24. Whitby, K. T., and Clark, W. E., "Electric Aerosol Particle Counting Size Distribution Measuring System for the 0.015 to 1μ Size Range," Tellus, XVIII(2), 573-86 (1966).

The terms α_v and α_s are called volume and surface shape-factors, respectively.

One method for determining α_v and α_s for test dust samples would employ results of other characterization tests. These tests include optical counting of average Martin's diameter on a field of N particles ($\sim$400), air pycnometer measurement of crystal density, and BET measurement of the surface area in m^2/g. The average Martin's diameter is defined as the average of the diameters of a specified number of particles along a line equally dividing the bulk of the particles.

With a measure of crystal density, e, the total weight of the equivalent spheres can be calculated;

$$W_{sph} = \pi/6 \; d_s^3 \; (N) \; (e)$$

The actual surface area in m^2/g can then be determined by the BET method. This value S_{BET}, would then be normalized to the weight of the N equivalent spheres and then divided by the square of the statistical diameter to yield the value for α_s, the surface-shape factor. For example:

$$S_{BET} \; W_{sph} = S_{(N \text{ particles})}$$

$$\frac{S(W \text{ particles})}{d_s^2} = \alpha_s$$

The shape factor does not represent a measurement of shape, but from the manipulation of other property measurements, already used to characterize the particles, a constant indicative of particle shape can be obtained.

A classical method of surface area analysis is based on the BET theory.[25] This analysis is conducted by determining the quantity of gas necessary to form a single layer of gas molecules on the surface of the powder. One instrument utilized for this type of measurement is the Numinco-Orr Model MIC-103 Surface Area-Pore Volume Analyzer. Using nitrogen gas this instrument measures surface areas in the

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25. Brunauer, S., Emmett, P. H., Teller, E., "The Adsorption of Gases in Multimolecular Layers," Journal of American Chemical Society, 60, 309 (1938).

range from 1-200 m^2/g. Employing krypton, surface areas below 1 m^2/g are accurately measured. By measuring the rate of desorption of the gas, pore size distributions between pore radii of ten to several hundred angstroms can be measured.

B.3 CHEMICAL COMPOSITION

The chemical composition of test dusts simulating stationary source emissions is largely inorganic in nature, but in some cases (such as asphalt batch plants and coke oven emissions) a significant carbonaceous or organic chemical component can be present. Most analytical chemical laboratories possessing a full range and variety of sophisticated instrumental and wet chemical analysis capabilities can adequately characterize test dusts. The challenge represented in chemical characterization of particulate is to develop an analytical protocol that will yield the most information with the least amount of effort. One potential protocol is presented in Table 10.

The protocol accentuates instrumental rather than wet chemical analysis and depends to a large extent on the use of nondestructive analysis approaches, thereby minimizing the total amount of effort in both analysis and sampling. The nondestructive methods employed are x-ray fluorescence and x-ray diffraction techniques.

An instrument such as the EDAX-EXAM computerized x-ray fluorescence system is employed first for elemental analysis. The EDAX-EXAM system provides simultaneous analysis and display of all elements from fluorine to uranium, qualitative analysis in seconds, sensitivities to better than 0.1 $\mu g/cm^2$, quantitative analysis in minutes (% to ppm), matrix corrections of interelement effects and conversion of raw data to percentages, ppm, $\mu g/cm^2$, or other relevant concentration values.

The x-ray fluorescence elemental analysis is followed by molecular analysis of crystalline components by x-ray diffraction employing a General Electric XRD-3 diffractometer and Debye, Scherrer, and Laue back-reflection cameras. This system has recently been used in our laboratory to characterize the composition of particulate collected from an asphalt batch plant where high-vol filter samples were compared to baghouse dust and the filter, sand, and aggregate feed materials. The relative percentages of dolomite, quartz, and calcite were obtained via x-ray diffraction.

Table 10. PROTOCOL FOR ANALYTICAL ANALYSIS

I. Teflon Filter	II. Glass or Quartz Fiber Filter
Measure weight increase	Measure weight increase
Non-destructive XRF for metal and non-metal elements	Non-destructive XRF* for non-metal elements, e.g., S, and for some non-metal elements
	Non-destructive XRD* for crystalline components
	Portions of filter for micro C-H-N analysis - Oxidation and Pyrolysis Modes. Yielding total C, H, N. carbonate, nitrate, water, organic C-H-N
	Selected portions** of filter for wide-line NMR, SEM, electron probe, DTA, TGA, camera XRD, wet chemical sulfur analyses, IR

*Non-destructive XRF and XRD analyses of particulate on filters are optional, but recommend for initial studies.

**Measurements to be made on selected specimens, if necessary, after evaluation of basic XRF, XRD, and C-H-N analyses.

XRF - X-ray fluorescence
XRD - X-ray diffraction
NMR - Nuclear magnetic resonance
SEM - Scanning electron microscope
DTA - Differential thermal analysis
TGA - Thermogravametric analysis
IR - Infrared

Following these nondestructive analyses the samples are analyzed using an F&M Model 185 CHN Analyzer. Determinations of total carbon, organic hydrocarbon, inorganic carbon, nitrogen, and water are made by operating the micro carbon-hydrogen-nitrogen analyzer in two modes, (a) oxidation (normal), and (b) pyrolytic (non-oxidation). Measurements with the analyzer are made by sequential catalytic oxidation and reduction processes which permit gas chromatographic separation and detection of CO_2, H_2O, and N_2. The combustion is performed in a furnace at 1070°C. Approximately 0.5 mg to 10 mg samples yield accurate measurements of carbon, hydrogen, and nitrogen down to 0.1% or less.

By operating in the oxidation mode, total C (organic and inorganic), total N (organic and inorganic), and total H (organic and inorganic, as hydrate, adsorbed H_2O, and hydroxide) are obtained. In pyrolysis (1070°C) mode without oxidizing catalyst, CO_2 from carbonate, N_2 from nitrates, and H_2O from hydrates, adsorbed H_2O, and hydroxides are measured.

Although the above tests are the basic measurements, other optional measurements are also available. We have studied adsorbed and hydrated water phenomena by wide-line proton nuclear magnetic resonance, differential thermal analysis, thermogravimetric measurements and pyrolysis. The DTA, TGA, and pyrolysis (weight-loss) measurements with auxiliary monitoring of H_2O by a sensitive hygrometer (Panametric Model 1000) and by gas chromatographic measurements (directly with thermal conductivity detector and carbon molecular sieve or conversion to acetylene and flame ionization detection) are alternate thermal analysis methods. By changing the matrix gas (inert gas to air) in these thermal methods, measurements of hydrocarbons, fixed carbon, and water can be made. The major limitation of the TGA, DTA, and pyrolysis (weight-loss) measurements is the continuous evolution of H_2O throughout the temperature range 100-1000°C. Wide-line NMR is a nondestructive technique and can be used to estimate the total water content and also aid in establishing the nature of the water bonding to the particulate.

Additional measurements by micro-infrared absorption techniques can aid in defining the water, carbonate, nitrate, and hydrocarbon contents of both crystalline and non-crystalline particulate.

B.4 DENSITY

Crystalline density of test dusts can be measured with a Beckman Air Comparison Pycnometer. The apparatus consists of two equal-volume cylinders with a sample chamber provided

in one of the cylinders for insertion of the test powder. Pistons in both cylinders permit volume changes. The pistons in both reference and sample cylinders are advanced so as to maintain a zero differential pressure between the cylinders. Due to the presence of the powder sample, the volume change in the specimen chamber is smaller by a factor equal to the volume of the preweighed dust sample. A schematic of the pycnometer is presented in Figure 15 (ASTM D2856-70).

In previous studies of finely divided powders[26,27,28] the measurement of bulk, apparent, and fluid densities of powder samples were obtained employing relatively simple, but meaningful laboratory procedures.

Apparent density is defined as the weight of a sample of powder divided by the volume it occupies when first placed in a container. Bulk density is defined as the weight of powder divided by the minimum volume into which it can be compressed by vibration or tapping. Fluid density is defined as the weight of the powder divided by its volume after having been shaken with air and allowed to settle to its fluid volume.

The procedures for measuring these densities are as follows:

Fluid density - Approximately 5 g of a material are sealed into a 50-ml graduated cylinder. The cylinder is rocked back and forth in a horizontal position to fluidize the sample and then rapidly placed in an upright position. The volume as the meniscus is first detected in the cylinder is taken as the fluid volume, and this figure is divided into the sample weight to find the fluid density.

Apparent density - After being fluidized, the sample is allowed to settle until no further evidence of settling is observed. The volume is taken as the apparent volume; dividing into the sample weight yields the apparent density. The fluid density and

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26. Hedley, W. H. et al., op. cit., ref. 20.

27. Binning, R. C., et al., "Physical and Colloid Chemical Research on Agents," Final Report, contract DA18-035-AMC-136(A), U.S. Army, Edgewood Arsenal, January 1969.

28. Snyder, A. D., et al., "Physical and Colloid Chemical Research on Agents," Final Report, contract DAAA-15-68-C-0316, U.S. Army, Edgewood Arsenal (1970).

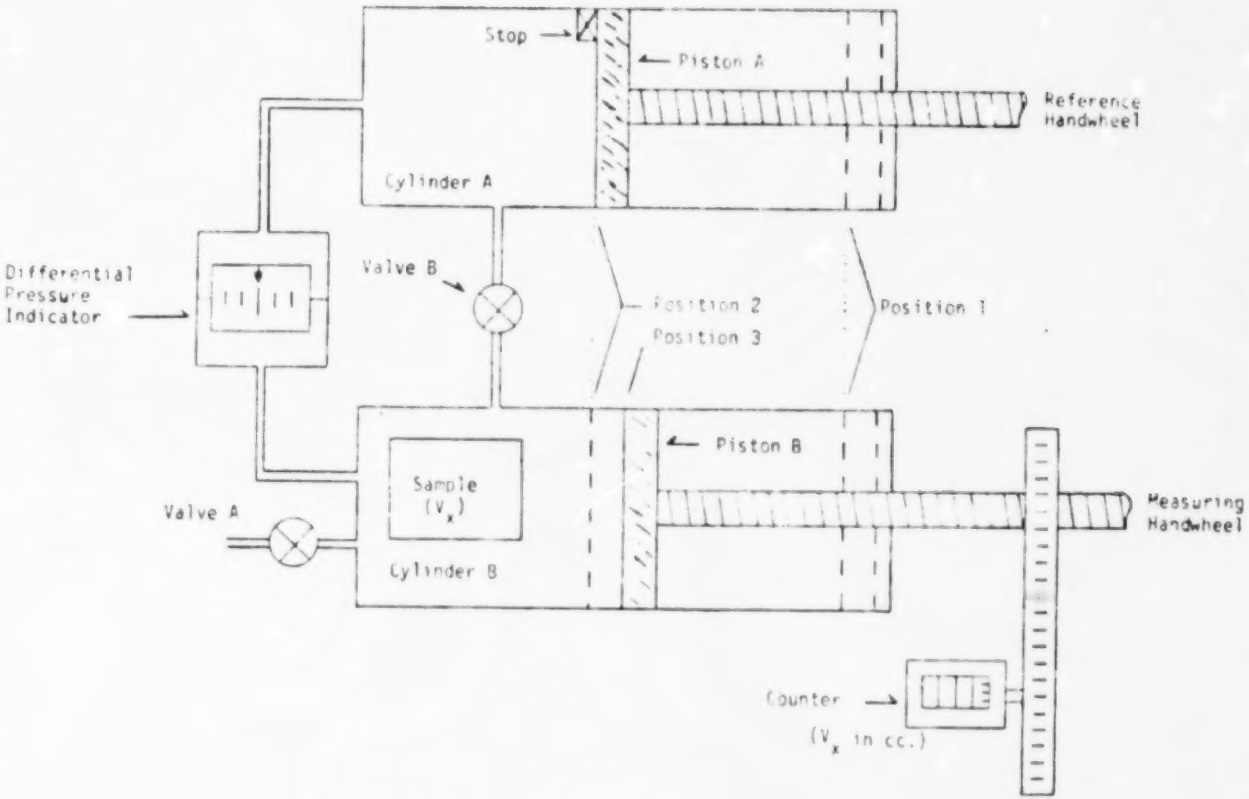

Figure 15. Air Pycnometer-Piston Action

apparent density are determined a number of times (at least three determinations) and average values calculated.

Bulk density - The graduate containing the sample is placed on a Cenco-meinzer sieve shaker (control setting of 6) for approximately 10 minutes or until a minimum volume is occupied by the powder. This value is taken as the bulk volume. Dividing it into the sample weight yields the bulk density. This determination is repeated by fluidizing the sample, compacting it on the shaker, and reading the volume at least three times to yield an average bulk density.

B.5 WETTABILITY AND MOISTURE CONTENT

B.5.1 Wettability

The classical method of determining wettability is to measure the contact angle of a drop of liquid with a surface of the material in question. A contact angle goniometer instrument can be applied to the measurement of the wettability of test powders. For these measurements a disc of the powder is pressed in order to develop a surface for contact angle measurement. The repeatability of the measurement requires assessment due to uncertainties in reproducibly producing the compacted powder surfaces.

Another method for determining the wettability of test dusts is to measure either the velocity of rise of a liquid in capillaries packed with powders or the total time required for a liquid to rise a designated height.[29]

A method for qualitative determination of wettability was developed by Monsanto Research Corporation.[30] Briefly, the test consists of adding the samples of powder to vials containing liquids of various surface tensions and determining which solutions wet the powder. The solutions are prepared by adding different amounts of detergent to water. The majority of studies were done with biodegradable Sparkleen, but other surfactants were also used.

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29. Vandergrift, A. E., et al., op. cit., ref. 6.

30. Hedley, W. H., et. al., op. cit., ref. 20.

The test procedure for the determination of the wettability by this method is as follows: eight sample vials are cleaned and numbered from 1 to 8. Distilled water (20 milliliters) is placed in the first vial. Vials 2 through 8 contain 20 milliliters of a solution of varying amounts of surfactant to yield surface tensions from 47 to 68 dynes per centimeter. (The surface tension of pure water is 72 dynes per centimeter). Approximately 0.5 g of powder is added to each vial and and all vials are shaken for 5 min on a Cenco Meinzer sieve shaker. After this time the amount of turbidity in each of the sample tubes is observed visually. Samples of powder with a high wettability show turbidity in nearly all of the sample vials. Those with low wettability show turbidity only in the vials with the lower surface tension (the higher numbered vials of the series). The identity of the lowest numbered vial showing turbidity is recorded. High numbers in this test indicate a low degree of wettability. The results obtained on 13 samples using both Sparkleen and Tween 80 detergents are shown in Table 11. The surface tension of each of the various samples is also shown in this table.

B.5.2 Moisture Content

Moisture content for collected test dusts may be determined using physical, chemical, or electrical techniques. An example of each type is described below.

The oldest and most common analytical method for determining moisture content consists of heating the sample to ensure complete drying. The moisture content is calculated based on the loss of weight between the original and dried sample. Care must be taken to ensure that the loss in weight is due only to water loss and not caused by evaporation of other volatile components in the dust.

The moisture content of fine powders can be determined chemically using a modified Karl Fisher titration method. A 1-gram sample of the powder is added to dry methanol in a titration vessel and a measured quantity of Karl Fisher reagent added. The excess reagent is immediately back-titrated with a standard solution of water in methanol. The end point is determined electrometrically using a dead-stop end-point technique.[31]

An instrumental technique using a type 26-321A Moisture Analyzer from Du Pont Instruments can also be used for moisture content analysis. The instrument measures moisture

31. Strauts, C. R. N., Gilfellan, J. H., and Wilson, H. H., Analytical Chemistry, Vol. II, Oxford, Great Britain, The Clarendon Press, 1966, p. 253.

Table 11. WETTABILITY DETERMINATION RESULTS BY CYLINDER METHOD

Sample Powder	Lowest Numbered Vial Showing Turbidity: Sparkleen Vial No.	Sparkleen γ (dynes/cm)	Tween 80 Vial No.	Tween 80 γ (dynes/cm)
1	7	49.0	6	48.5
2	6	52.5	8	45.8
3	8	47.0	8	45.8
4	8	47.0	8	45.8
5	3	64.0	3	57.7
6	6	52.5	4	54.3
7	6	52.5	6	48.5
8	8	47.0	7	47.5
9	8	47.0	8	45.8
10	1	72.0	3	57.7
11	1	72.0	3	57.7
12	6	52.5	6	48.5
13	3	64.0	6	48.5

content in a powder sample using coulometric principles. The sample to be tested is placed in an oven where the temperature is raised to drive off any water present. Dry nitrogen carrier gas flowing through the oven sweeps the moisture into an electrolytic cell where it is electrolyzed. The cell consumes an amount of current corresponding to the quantity of moisture. The electrolysis current drives an integrator, and because the cell current is integrated as a function of time, a measurement of the total moisture present is made which is independent of the carrier gas flow rate.

The sensitivity of the instrument is 0.1 µg with an accuracy of 2% of the reading or ±20 µg H_2O, whichever is greater. The dynamic range of the moisture analyzer is 0.1 µg to 100 mg of H_2O. A block diagram of the instrument is presented in Figure 16.

This procedure is applicable for moisture which is removed from the dust samples at temperatures less than 200°C (the upper temperature limit of the moisture analyzer).

An alternate method would be required for determination of water of crystallization or bound water that is not evolved below 200°C. The F&M Model 185 CHN Analyzer can be adapted for this purpose. Hydrogen analysis of (1) powder samples burned under oxidizing catalyst conditions and (2) powder samples heated at 450°C in the absence of an oxidizing catalyst can be employed to estimate the volatile hydrogen present in the form of moisture.

B.6 SOLUBILITY

For the purpose of characterizing test dusts water solubility is of concern. A convenient method for determining solubility is by successive water extraction of a weighed quantity of dust using a Soxhlet extractor. The rate of extraction should be set at 15 to 20 times per hour and continued for 4 hours (ASTM D-1739 and D-494). The solubility can be calculated after equilibrium solubility is attained by drying the sample to constant weight and calculating the loss in weight due to solubilized powder. An alternate method is to collect the extracting water and evaporate to dryness in a tared petri dish until constant weight is achieved. The increase in weight of the petri dish would yield the solubility of the test sample.

B.7 HARDNESS, ABRASIVENESS, AND GRINDABILITY

The hardness of test dusts or material from which test dusts originate can be determined using either research-oriented

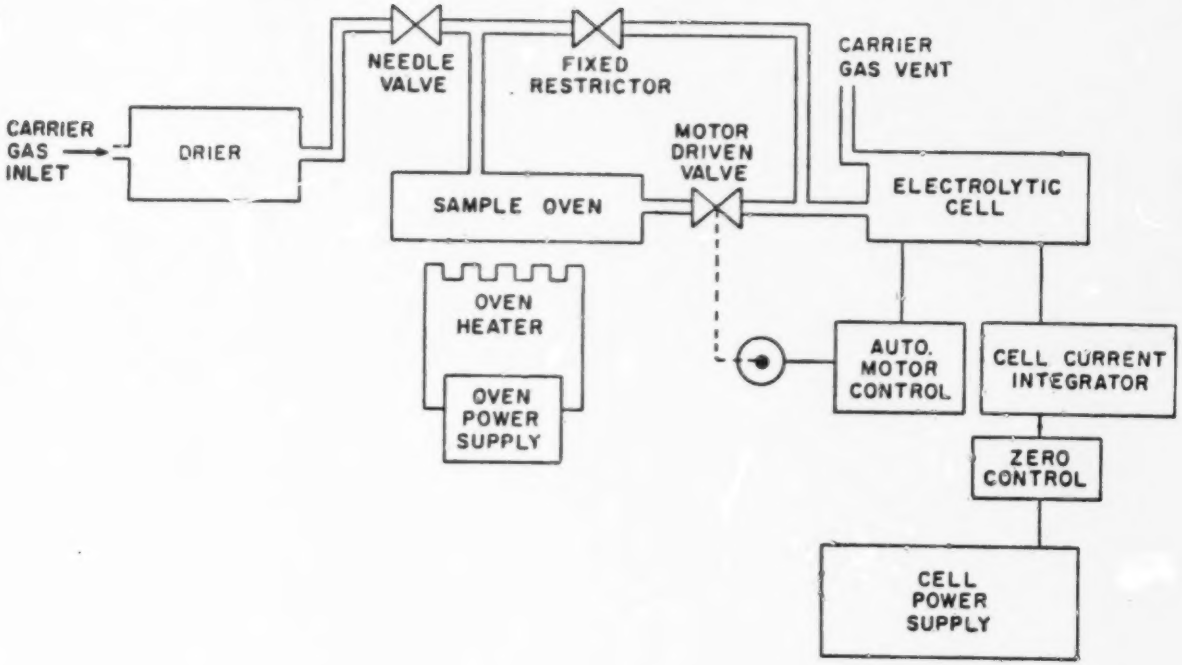

Figure 16. Block Diagram Moisture Analyzer

or end-use-oriented test methods. The research method most widely used is the standard test method for microhardness of materials (ASTM E384-70). In this test (microindentation hardness) a calibrated machine forces a diamond indenter of specific geometry, under a test load of 1 to 100 gf (grams force), into the surface of the test materials. After indentation the mean diagonal produced on the test specimen is measured by use of a microscope mounted on the machine. The hardness can be measured with either Knoop or Vickers indenters. The Knoop hardness number is expressed as:

$$HK = \frac{14229\ P_1}{d_1^2}$$

where HK = the Knoop hardness

P_1 = load, gf, and

d_1 = length of the long diagonal, μm

For Vickers hardness tests the mean length of all diagonals is employed and the hardness number is expressed as:

$$HV = \frac{1864.4\ P_1}{\bar{d}_1^2}$$

where HV = the Vickers hardness

$\bar{d}_1$ = mean diagonal of indentation, μm

The abrasive effect of fine particles on materials of construction cannot be easily separated from the corrosive effect of the carrier gas and dust particles. Corrosiveness is the result of a chemical reaction primarily due to carrier gas composition, with particulate composition contributing a small portion. Abrasiveness is a result of the inertial collisions between many small particles and the walls of the equipment. A test for abrasiveness would be similar to that for corrosiveness. In fact, the test described for corrosiveness could be used as a combined abrasiveness/corrosiveness test.

The grindability of materials is often measured using the Hardgrove method.[32] In this test a 50-gram sample of dried material (such as coal) sized to minus 16 to plus 30 mesh is placed in a mortar of the test machine. A motor then turns the grinder through 60 revolutions and the sample is

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32. Salisbury, S. K., Section 27 "Pulverizers," Kent's Mechanical Engineer's Handbook, 12th Edition, Wiley Engineering Handbook Series, New York, N.Y. (1960)

removed and screened. The quantity of sample passing a 200-mesh sieve is used to determine the Hardgrove grindability index by the following empirical formula.

$$G = 6.93\ W + 13$$

where W = weight (grams) passing the 200-mesh sieve. This test is used as a primary method for assessing the grindability of coals and to predict the performance of a particular type mill with respect to its ability to grind the coal.

B.8 CHARGE ANALYSIS

Methods for charge analysis could be either that of Gillespie and Langstroth[33] or that of Kunkel and Hansen[34] which employ a low velocity laminar stream of dilute aerosol and determine the distribution of both particle size and particle change.

A schematic view of Gillespie's charge analyzer is illustrated in Figure 17. The Gillespie apparatus measures charge distribution and particle size distribution by examination of the positions along the length of the microscope slides on which particles of different size have been deposited due to the electric field. Uncharged particles pass through the apparatus, and are precipitated and examined under the microscope. The charge analysis is carried out by considering the interplay of the equations of motion on a particle of known radius and initial velocity as it enters an electric field of known strength.

The apparatus of Kunkel and Hansen does not depend upon examination of the deposit, but photographs the particles as they fall down into a field of known strength. The particle sizes are measured on enlargement of the film from the velocities measured in falling through an uncharged field. The charges are calculated from the particle trajectories in the charged field, which are filmed by light interruption employing a rotating disc in front of the light source. This method appears to be more convenient, but was not applicable to diameters smaller than 1μ in Kunkel's work.

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33. Gillespie, T. and Langstroth, G. O., "An Instrument for Determining the Electric Charge Distribution on Aerosols," Canadian Journal of Chemistry, 30, 1056-68 (1952)

34. Kunkel, W. B. and Hansen, S. W., "A Dust Electricity Analyzer," Review of Scientific Instruments, 21, 308-14 (1950).

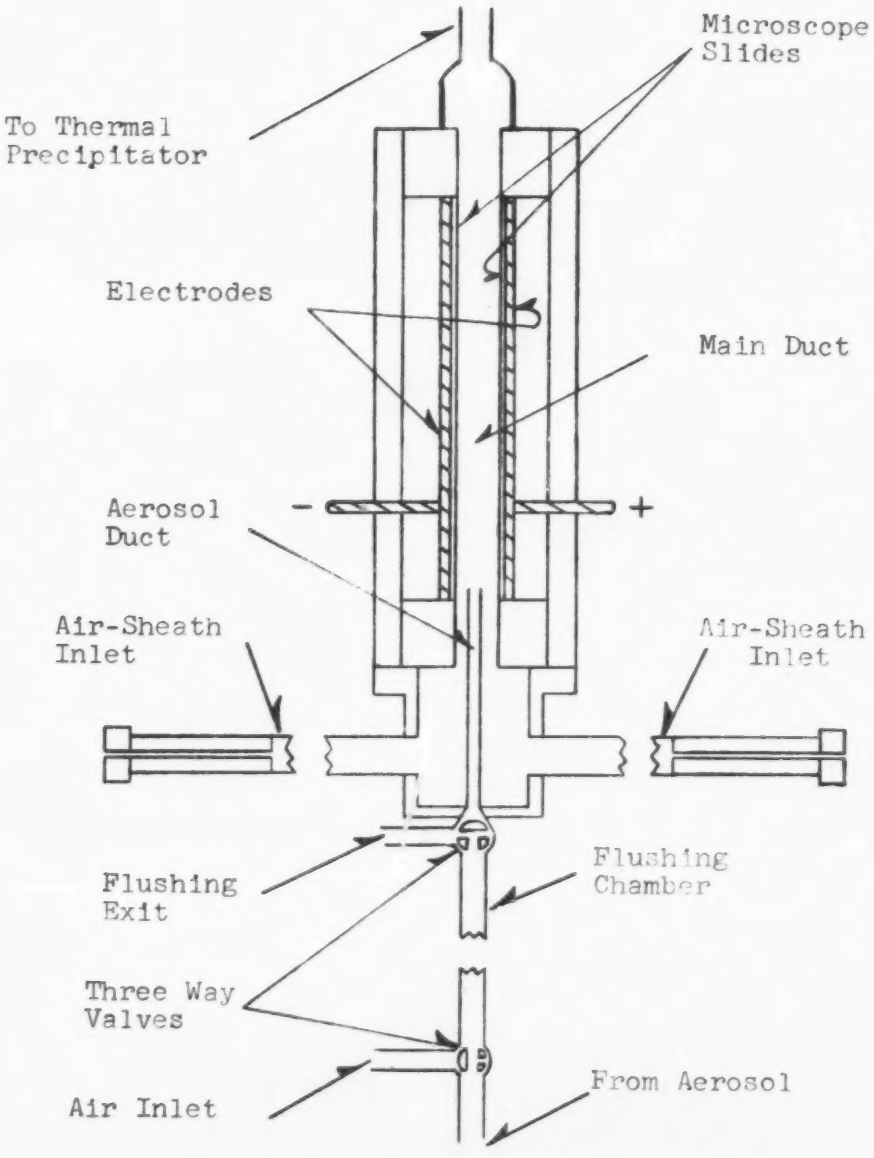

Figure 17. Gillespie Apparatus for Measuring Particle Size and Charge

B.9 DIELECTRIC PROPERTIES

Electrical properties are known to directly influence the behavior of fine powders because they relate basically to the charging and relaxation times for charge transfer. Quantitative determination of particulate resistivity can be obtained using several techniques utilizing a variety of equipment. Both laboratory and *in situ* measurement techniques are available, but *in situ* determination is the preferred method due to the predominance of surface conductivity at typical lower flue gas temperatures (below approximately 350°F). At these temperatures adsorbed species from the flue gas control particulate resistivity. Flue gas conditions may be simulated in a laboratory, but the potential for chemically active compounds adsorbed on the particles to modify the particulate properties between time of collection and measurement is great.

The resistivity of fine dusts may be obtained in a laboratory situation and may be used to characterize a dust sample. The standard technique for obtaining resistivity measurements in the laboratory is described in the American Society of Mechanical Engineers Power Test Code 28, Determining the Properties of Fine Particulate Matter.

However, the measurements may not be representative of the values that exist in an actual flue gas due to a difference in the conditioning effects of the carrier gas composition. The resistivity obtained in the laboratory may frequently be two to three orders of magnitude higher than *in situ* measurements.[35] To obtain representative values of particle resistivity for a flue gas, the measurement must be performed *in situ*. Equipment similar in principle to that used in the laboratory may be utilized for this type of measurement.[36] *In situ* resistivity measurements are made under conditions in which the only atmosphere to which the dust is exposed is that present in the process. This eliminates uncertainties in attempting to duplicate the gaseous conditions and generally gives more reliable and reproducible results than those obtained by laboratory techniques.

A number of instruments are available for making *in situ* resistivity measurements; point to plane probe, cyclone resistivity probe, Kevatron electrostatic precipitator

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35. Vandergrift, A. E., et al., op. cit., ref. 6.

36. White, H. J., Industrial Electrostatic Precipitation, Addison-Wesley Publishing Co., Inc., Reading, Massachusetts (1963).

analyzer, and Lurgi electrostatic collection resistivity device, with the point to plane probe preferred. The instruments differ fundamentally in the method of sample collection, degree of compaction of the dust sample, the values of the electric field and current density used for measurement, and the method of maintaining thermal equilibrium in the measurement cell. These variances in operation cause differences in the sample characteristics and consequently differences in resistivity measurements For example, the collection efficiency for fine particles varies among the different types of measurement devices thereby biasing the measurement sample toward larger particles to a varying extent. The resulting resistivity measurement is correspondingly biased.

Figure 18 is a schematic diagram of a typical *in situ* resistivity probe. The apparatus consists of a point-plane cell at the end of the probe, which is inserted into the duct through openings of from 2-1/2 inches to 4 inches diameter. When a voltage sufficient to generate a corona is applied to the cell, dust is precipitated onto the plate. After sufficient time has elapsed to collect a dust layer, the point-plane disc is lowered onto the dust layer and the current and voltage are measured. The probe is then removed and the dust thickness measured. Resistivity can then be calculated from the dimensions of the probe, thickness of the dust layer, and the electrical data. Thermocouples on the probe are used to measure temperature.[37]

B.10 CORROSIVENESS

Corrosiveness is primarily due to carrier (flue) gas components. Particle composition contributes a minor effect. Laboratory experiments to determine the corrosive contribution of the fine particles and adsorbed gas species can be performed, but to determine the true corrosive nature of the entire flue gas, tests must be conducted in the flue gas. There is no standard or preferred method for performing a corrosion test.[38] The method must be designed to suit the purpose of the test. For particulate emission control equipment the purpose of corrosion testing would be to aid in the selection of materials of construction.

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37. Oglesby, S. and Nichols, G. B., "A Manual of Electrostatic Precipitator Technology, Part I - Fundamentals," prepared for NAPCA, contract CPA 22-69-73, Cincinnati, Ohio, 25 August 1970.

38. Perry, J. H., Chemical Engineers' Handbook, 4th edition, McGraw-Hill, Inc., New York, N.Y. (1963).

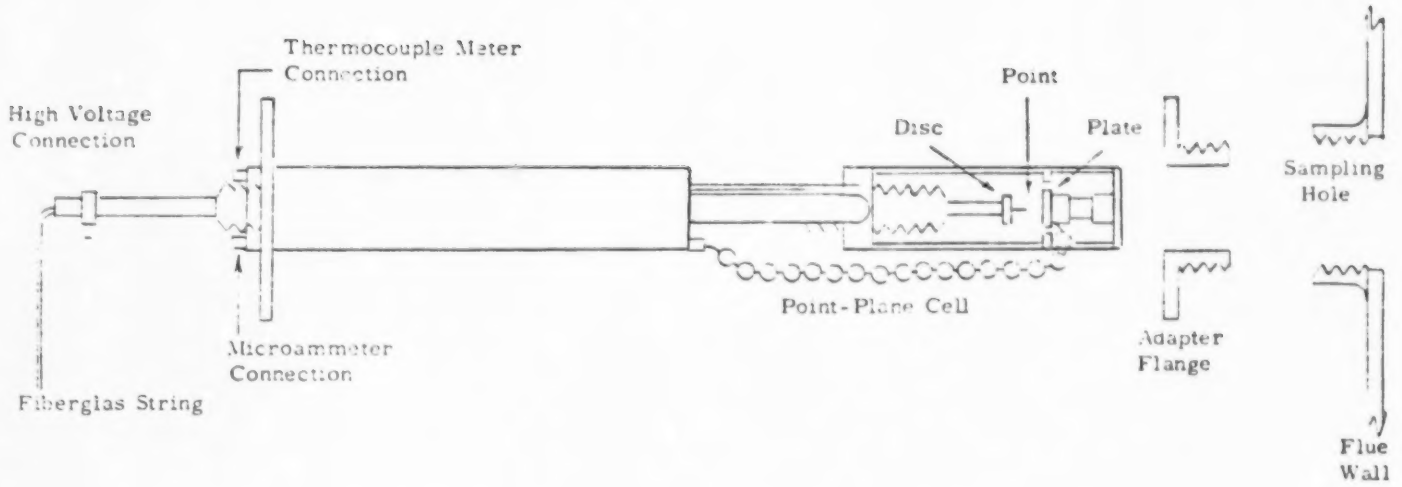

Figure 18. Resistivity Probe

A series of experiments using a variety of test materials (e.g., various grades of steel, plastic coupons, etc.) could be designed to provide means for comparison. In the laboratory these experiments could be performed by making a wet slurry and inserting the different samples for designated time periods. The tests could also be accelerated by elevating the temperature of the dust slurry. For flue gas corrosiveness testing the different test materials could be mounted in the gas stream and exposed to the corrosive atmosphere for predetermined periods of time.

Several potential methods of measuring the extent of the corrosion may be utilized. Direct observation is a simple technique but only qualitative in nature. Mechanical tests including dimensional measurement, change in weight measurement, or measurement of a change in a physical property (e.g., tensile strength) provide a quantitative measure of corrosiveness. For laboratory measurements a simple indication of the corrosive nature of a dust slurry is the pH. One final potential indicator of the extent of corrosion on a test sample is a change in the electrical properties of the sample.[39]

B.11 OPTICAL PROPERTIES

Refractive index is the physical property most frequently associated with measurement of the optical properties of macrosized samples of pure materials. However, there is little information in the literature on determination of the refractive index of fine particles of irregular shape and varied composition.[40]

The complex refractive index, m, may be defined in terms of two optical constants, n, the refractive index, and k, the extinction coefficient:

$$m = n(1-ik)$$

These constants are not measured directly, but are calculated from reflectivity measurements. In principle, the method for measuring the complex refractive index of a substance consists of measuring characteristics of reflection at various angles of incidence. If the measured values of the reflection characteristic for plane polarized light

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39. Kallen, H. P., "Corrosion," a Power special report, New York, N.Y., December 1956, pp 73-108.

40. Willis, C., "The Complex Refractive Index of Particles in a Flame," Journal of Physics, Series 2, Part D, Vol 3, 1944-56 (1970).

of azimuth, ρ, at angles of reflection θ_1 and θ_2 are I_1 and I_2, then:

$$I_1 = f(n,k,\theta_1,\rho)$$

and

$$I_2 = f(n,k,\theta_2,\rho)$$

where f is a function obtained from the appropriate Fresnel equations for the reflections. The simultaneous solution of the algebraic relations represented above cannot be obtained directly for n and k, the optical constants, but must be solved indirectly either graphically or by a least squares computer analysis.

The complex refractive index for a particle can also be defined as the complex refractive index of the material in the form of a sphere having the same scattering pattern as the sample particle. This definition, although not a universal parameter, is more useful in practice than the actual refractive index of the material of the particle.

Some effort has been made to determine the refractive index of some atmospheric aerosols. Volz[41,42] has determined the complex refractive index for a variety of fine particulate matter (atmospheric water-soluble substances collected from rainwater, ammonium sulfate, Sahara dust, volcanic pumice, and flyash) using the potassium bromide disc technique. Reflection data from discs of pure aerosol are used to obtain the real part of the refractive index while potassium bromide discs with about 1% aerosol are used to determine the imaginary component. This technique may be utilized for refractive index determination for fine particles from industrial sources.

However, as a result of his work with silicon dioxide particles and pulverized coal particles, Willis[32] claims that a particle stream does not have the same value of complex refractive index as does a solid or compacted macrosized sample of the same material. A schematic of the optical arrangement utilized in his study appears in Figure 19. Data were collected for both ambient and elevated (1700°K) temperatures without observation of any significant change

41. Volz, F. E., "Infrared Refractive Index of Atmospheric Aerosol Substances," Applied Optics, 11(4), 564-8 (1972)

42. Volz, F. E., "Infrared Optical Constants of Ammonium Sulfate, Sahara Dust, Volcanic Pumice, and Flyash," Applied Optics, 12(3), 755-9 (1973).

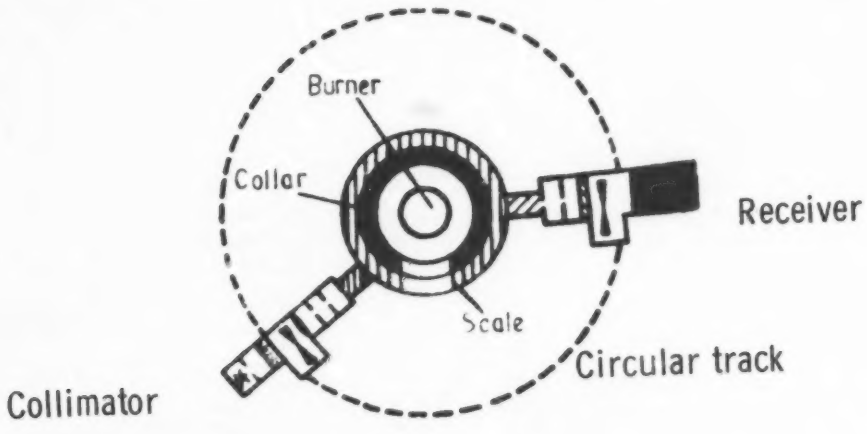

Figure 19. Schematic of Optical Arrangement

in the complex refractive index. With refinement this type of device would be suitable for the characterization of industrial fine particulate.

Since the refractive index is only important in its influence on the measurement of particle size, the determination of the actual refractive index is less critical than knowing the effect of that refractive index on size measuring techniques. For this purpose a relatively simple characterization technique could be developed. Assuming optical size measurement devices are similarly affected by a particle's refractive index, the behavior of a particle in any of these type devices could be predicted by its behavior in one of them. Calibration curves for particles of varied refractive index could be generated for one specific instrument. Then collected industrial particles of several known sizes could be tested to determine their "apparent" refractive index. The particle's actual refractive index may not be known, but its behavior is more important for characterization purposes.

Two assumptions must be accepted for this type of measurement to be meaningful. The refractive index must be the only variable influencing an apparent change in the size measurement, and the particles sampled must be typical of all the collected particles. The result of these measurements will be a curve showing refractive index as a function of particle size for the material being tested.

B.12 MAGNETIC PROPERTIES

There are two types of magnetic susceptibility. Substances on which the molecules are arranged essentially at random (gases and liquids) are magnetically isotropic, i.e., the magnetic susceptibility is the same in all directions. Solids too may be effectively isotropic if their components are randomly oriented. The magnetic susceptibility of these types of materials is referred to as the average susceptibility. The magnetic susceptibilities along each axis (often unequal) are referred to as principal susceptibilities. Since the magnetic susceptibility of test dusts would be measured on bulk randomly oriented quantities, average susceptibility measurements would be appropriate.

There are many methods available for measurement of magnetic susceptibility. Choice of method depends on the problem to be solved. There is no single method of universal applicability. Several techniques are described in the literature.[43,44,45,46]

One method applicable to the testing of finely divided powders is the Gouy method. The principle by which this method operates is shown in Figure 20. A cylindrical sample is suspended with one end in a uniform magnetic field and the other end in a region where the field is negligible. The force exerted on the sample by the magnetic field is measured by suspending the cylinder from the arm of a sensitive balance and finding the change in weight due to the field.

Instrumentation suitable for application to determining magnetic susceptibility of fine particulate dusts is available.[42,43]

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43. Bhatnagar, S. S. and Mathur, K. N., Physical Principles and Applications of Magnetochemistry, Macmillan and Co., Ltd., London, 1935.

44. Trade Literature, LDJ Electronics, Inc., Troy, Michigan, Vibrating Sample Magnetometer.

45. Trade Literature, Princeton Applied Research, Princeton, New Jersey, Vibrating Sample Magnetometer.

46. Selwood, P. W., op. cit., ref. 11.

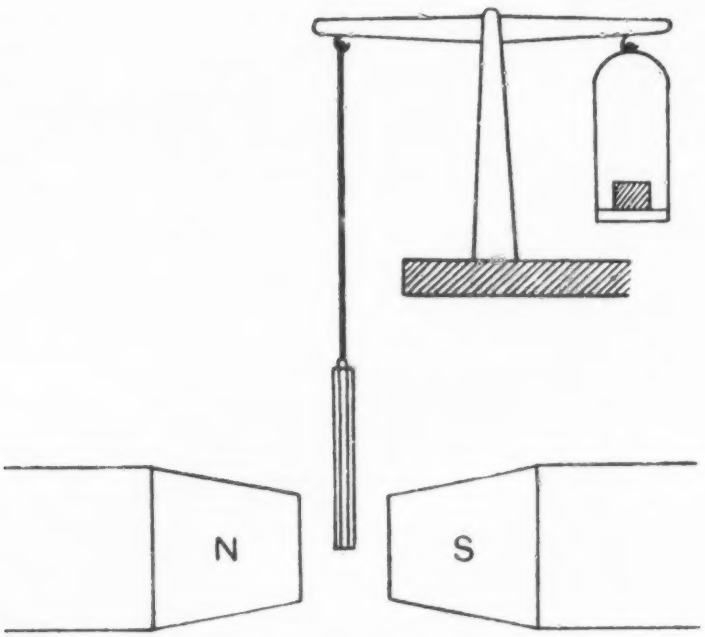

Figure 20. Principle of Gouy Balance

APPENDIX C

TYPICAL FLUE GAS CHARACTERISTICS FOR INDUSTRIAL SOURCES[47]

Key to Typical Flue Gas Characteristics

Solids

Particle size - weight % < size (micron)
Solids loading - grain/SCF
Chemical composition - component - weight %
Bulk density - lb/ft^3
Particle density - g/cm^3
Electrical resistivity - ohm·cm (laboratory measurement)
Moisture content - weight %
Toxicity - self explanatory
Solubility - self explanatory
Wettability - self explanatory
Handling characteristics - self explanatory

Carrier Gas

Flow rate - M scfm
Temperature - °F
Moisture content - volume %
Chemical composition - component - volume %

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47. Vandergrift, A. E., et al.,op. cit., ref. 6.

Pulverized Coal Combustion (electricity generation)

Particle size - 15<3, 25<5, 42<10, 65<20, 81<40

Solids loading - 1.02 - 5.6 (mean 3.3)

Chemical composition - SiO_2 17-64 (average 43)
Fe_2O_3 2-36 (15)
Al_2O_3 9-58 (24)
CaO 0.1-22 (4)
MgO 0.1- 5 (1.0)
Na_2O 0.3- 4 (0.9)

Bulk density - 30-50

Particle density - 0.6-3.0 (average 2.3)

Electrical resistivity - 10^8-10^{13}

Moisture content - 0.23

Toxicity - not toxic but acidic

Solubility - contains H_2O soluble components

Wettability - difficult

Handling characteristics - difficult, agglomerates

Carrier Gas

Flow rate - 292-402

Temperature - 251-314.5

Moisture content - 5.9-8.0

Chemical composition - CO_2 12.5-14.9
O_2 4.2- 6.6
N_2 balance
CO 5-69ppm
NO_x 161-526ppm
SO_2 1080-1780ppm
SO_3 3-66ppm

Stoker Fired Coal Combustion

Particle size - 11<10, 23<20, 42<44

Solids loading - 1.5-2.3 (average 1.9)

Carrier Gas

Flow rate - 49-367

Temperature - 396-426 (average 411)

Moisture content - 7.4-7.8 (average 7.6)

Chemical composition - CO_2 12.1

O_2 6.6-6.9

N_2 balance

CO 13-29ppm

NO_x 430ppm

SO_2 1280-1380ppm

SO_3 52-58ppm

Basic Oxygen Furnace (iron & steel)

Particle size - 85-95 <1 (count median diameter 0.012, mass median diameter 0.095)

Solids loading - 2-10

Chemical composition -

Fe_2O_3	90
FeO	1.5
Mn	0.4-1.5
SiO_2	1.3-2.0
Al_2O_3	0.2
CaO	3-5
MgO	0.6-1.1

Particle density - 3.44

Electrical properties - resistivity peak between 300-400°F

Solubility - Fe_2O_3 soluble - 10% HCl

Wettability - difficult to wet

Handling characteristics - abrasive

Carrier Gas

Flow rate - 35-250

Temperature - 560-3000 depending on utilization of waste heat boiler

Chemical composition -

	Before combustion with aspirated air	After combustion with aspirated air
CO_2	5-16	0.7-13.5
CO	74-91	0-0.3
N_2	3-8	74-78.9
O_2	- - -	balance

Open Hearth Furnace (iron & steel)

Particle size - 50<5

Solids loading - 0.1-3.5

Chemical composition - Fe_2O_3 85-90
SiO_2 0.9-1.6
Al_2O_3 0.5-0.7
CaO 0.85-1.0
MnO 0.6
P_2O_5 0.5-1.2
S 0.4-1.0

Particle density - 5.0

Electric properties - f(temperature) resistivity peak ∿300°F

Solubility - Fe_2O_3 soluble 10% HCl

Wettability - difficult to wet

Handling characteristics - abrasive

Carrier Gas

Flow rate - 25-100

Temperature - 460-1800 depending on utilization of waste heat boiler

Moisture content - 7-15

Chemical composition - CO_2 8-9
O_2 8-9
N_2 balance
SO_2 2-5ppm
SO_3 100-200ppm
NO_x 500-800ppm
Fluorides 0-300ppm

Electric Arc Furnace (iron & steel)

Particle size - highly variable, generally 60<5, BAHCO analysis: 68<5, 84<10, 95<20, 99<40

Solids loading - 0.1-2.2

Chemical composition - dependent on charge

Fe_2O_3	19-44
FeO	4-10
Cr_2O_3	0-12
SiO_2	2-9
Al_2O_3	1-13
CaO	5-22
MgO	2-15
MnO	3-12
FnO	0-44
CuO	0-1
NiO	0-3
PbO	0-4
C	2-4

Particle density - 3.8-3.9

Electrical properties - $6x10^5$ - $6.6x10^{13}$

Wettability - difficult

Handling characteristics - abrasive, fluid-cohesive, high angle of repose, will bridge and arch

Carrier Gas

Flow rate - 10-100

Temperature - 215-3000 depending on use of cooling techniques

Moisture content - 0.045 lb/lb dry gas

Chemical composition - mainly CO_2, CO, O_2, & N_2 - varies with operation; typically,

CO	8-85
CO_2	5-15
N_2	5-85

Metallurgical Coke Ovens (iron & steel)

Particle size - quency tower (Q.T.) 95-97>47

Solids loading - Q.T. 0.05-0.1 oven charging (O.C.) 1-15

Chemical composition - coke balls, coal dust, pyrolytic carbon

Carrier Gas

Flowrate - Q.T. 900M ft^3/quench O.C. 2.1M ft^3/charge

Temperature - Q.T. 140-150

Chemical composition - Q.T. - steam, air

O.C. - CO_2 2.2
O_2 0.8
N_2 8.1
CO 6.3
H_2 46.5
CH_4 32.1
C_2H_4 3.5
C_6H_6 0.5

Cement Plant (kiln)

Particle size - 15.5<5, 43<10, 64<20, 88<40; 30<5, 47.6<10, 66.7<20, 80.5<40

Solids loading - Dry 1-17 (average 6.4), Wet 1-14 (average 5.7)

Chemical composition -

CaO	39-50
SiO_2	9.8-19
Fe_2O_3	2-11
Al_2O_3	2-8
K_2O	2-8
Na_2O	0.9-11
MgO	1.3-2.5

Particle density - 2.6-3.2

Electrical resistivity - peak between 300-400°F

Solubility - CaO - soluble H_2O

CaO, SiO_2, Fe_2O_3, Al_2O_3

TiO_2 - soluble 10% HCl

Hygroscopic properties - will absorb H_2O

Handling characterisitcs - angle of repose 39°

Carrier Gas

Flow rate - dry 34-614 (stack conditions) wet 72-570 (stack conditions

Temperature - dry 150-845 wet 290-650

Moisture content - dry 1-2 wet 20-40

Chemical composition - CO_2, steam, O_2, N_2 , small quantities SO_2, NO_x, CO

CO_2	17-25
O_2	1-4
CO	0-2
N_2	75-80

Corrosivity - gases, 0-40% steam will corrode dead spots in piping

Municipal Incineration

Particle size - 89.2<44, 69<30, 47<20, 21<10, 6<5

Solids loading - dependent on operation 0.1-0.9 (avg. 0.4)
@ 12% CO_2

Chemical composition -		
	SiO_2	14-52
	Al_2O_3	8-28
	Fe_2O_3	4-19
	CaO	9-22
	MgO	2.8-3.4
	Na_2O+K_2O	3-10
	TiO_2	0.7-2.8

Particle density - 1.8-3.8

Electrical resistivity - peak at approximately 300°F
(10^9-10^{13})

Carrier Gas

Flow rate - 14-288

Temperature - 250-700

Chemical composition

CO_2, O_2, CO, N_2, H_2O

Typical:		
	CO_2	3.7
	O_2	13.0
	CO	0.2
	N_2	64.0
	H_2O	19

also aldehydes

Toxicity and corrosivity - dependent on waste composition

Iron Foundry

Particle size - 10<5, 22<10, 25<20, 35<50

Solids loading - usual range 1-3, average 1.2

Chemical composition - SiO_2 20-40
CaO 3-6
Al_2O_3 2-4
MgO 1-3
FeO (Fe_2O_3, Fe) 12-16
MnO 1-2

Particle density - mean vlaue 2.5-3.1

Electrical resistivity - peak at approximately 300°F

Solubility - CaO soluble in H_2O, CaO, SiO_2, Al_2O_3 soluble in 10% HCl

Wettability - difficult to wet

Handling characteristics - abrasive, cohesive, corrosive

Carrier Gas

Flow rate - 10.8-92

Temperature - 210-1410

Chemical composition - CO_2 2.8-12.3
O_2 11.8-12.7
CO 0-0.1
SO_2 0.002-0.013

Kraft Pulp Mill (recovery furnace)

Particle size - 50-85<2

Solids loading - 3-8 dry (mean 3.8)

Chemical composition - Na_2SO_4 - 14-90 (average 80)
Na_2CO_3 - 2.6-73 (11.2)
NaCl - 0.6-14 (high end sea water)
Na_2S - 3.3-5.4 (44)
Carbon, flyash

Resistivity - decreases with temperature increase and with moisture increase (10^9-10^{13})

Hygroscopic characteristics - hygroscopic

Handling characteristics - agglomerates, corrosive

Carrier Gas

Flow rate - 20-568 (average 432) standard ft^3/air-dried ton

Temperature - 270-650 (average 350)

Moisture content - 20-40

Chemical composition -

Typical orsat - CO_2 12.5
CO 0.1
O_2 7.6
N_2 79.8

Minor components - H_2S 130-935ppm
SO_2 1-350ppm
Methyl mercaptan 60-1,400 ppm
Dimethyl sulfide 0-125ppm

Corrosivity - corrosive due to S compounds

Asphalt Plants (rotary dryer)

Particle size - Highly variable, 13-91<10, 32-99<20, 55-100<44

Solids loading - extreme range 11-200 typical range 20-70 average - 30

Chemical composition - stone dust, flyash, soot, and unburned oil

Particle density - 2.6 (average value)

Carrier Gas

Flowrate - 7.7-46 (average 20) 3.9-24.6 (average 9)

Temperature - 85-525 (average 240)

Chemical composition - CO_2, NO_x, N_2, O_2, CO

APPENDIX D

LABORATORY TESTING OF REDISPERSIBILITY OF BULK POWDERS

The re-aerosolization apparatus developed by Monsanto Research Corporation is shown in Figure 21. It consists of a Pyrex tube 2-7/8 inches in diameter and 14 inches long with a glass frit (Corning Glassworks, Catalog No. 360 60) located near the bottom.

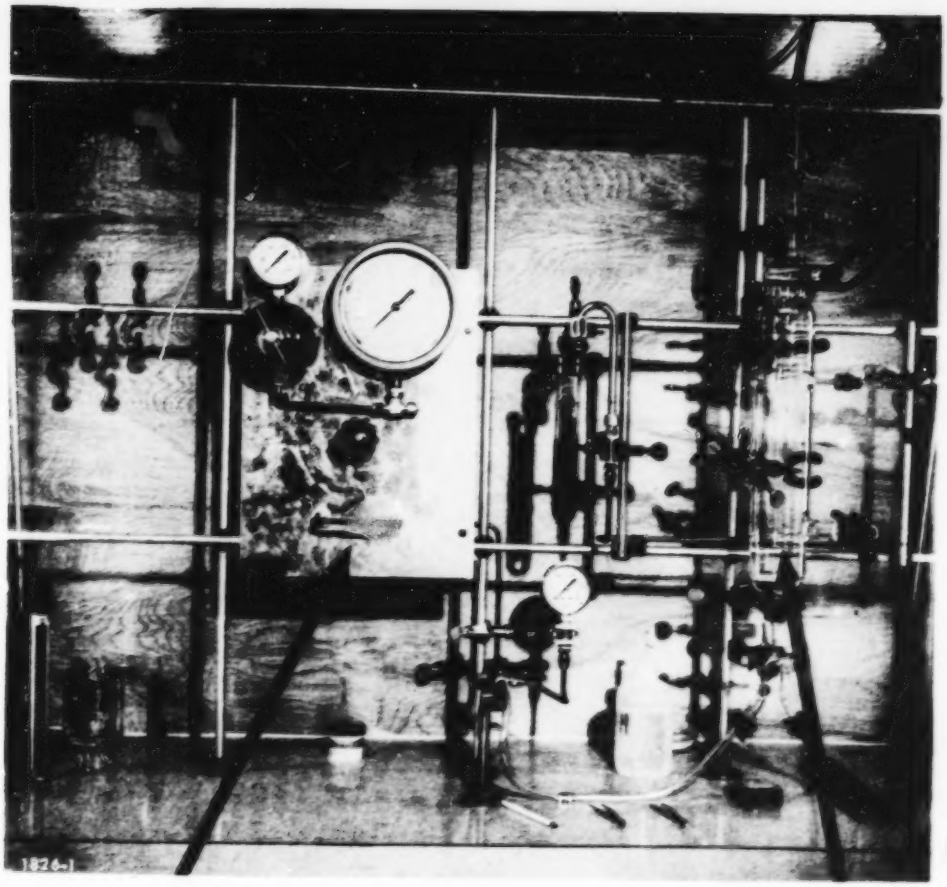
The sample is distributed on this frit and nitrogen is passed through, causing aerosolization. The upper portion of the apparatus contains a Pyrex filter holder (Millipore Filter Corporation, Catalog No. XX1004700), which holds 47-mm diameter RAWP 04700 Millipore filters having a small pore size. The re-aerosolized portion of the sample is collected on this filter for weighing. The apparatus, as assembled for use, is shown in Figure 21. This figure also shows the gauge and manometer used to indicate the back pressure on this system through the frit.

To perform a test, approximately 0.25 gram of powder is placed on the lower glass frit through one of the side arms of the apparatus. A small burst of nitrogen gas distributes the powder over the frit. The gas flow is then turned on slowly, and flow is increased (over a period of ten seconds) to a previously designated flow rate. The gas flow is continued for an appropriate time period to re-aerosolize the sample. The re-aerosolized portion is collected on the Millipore filter (previously tared). The percent (by weight) re-aerosolizability for each sample is computed as follows:

$$\% \text{ Re-aerosolizability} = \frac{\text{wt of sample collected on filter}}{\text{wt of sample initially added to apparatus}} \times 100$$

Use of this system on a number of powders of similar composition but differing particle size distributions and different surface coating permitted differentiation in the relative re-aerosolizability of powder samples.

A commercial product similar to the above apparatus is a stainless steel elutriation device which was developed for the U.S. Army by GCA Corporation, this system has been modified and tested at Monsanto Research Corporation's Dayton Laboratory. The major difference between the GCA and MRC instruments is that the dispersion forces in the stainless steel elutriator are somewhat greater.



Nitrogen
Metering System

Elutriation
Chamber

Figure 21. MRC Glass Reaerosolizability Apparatus

APPENDIX E

METRIC CONVERSION TABLE

1 inch = 2.54 cm

1 lb = 0.454 kg

1 grain = 0.0648 gram

1 ft^3 = 0.0283 m^3